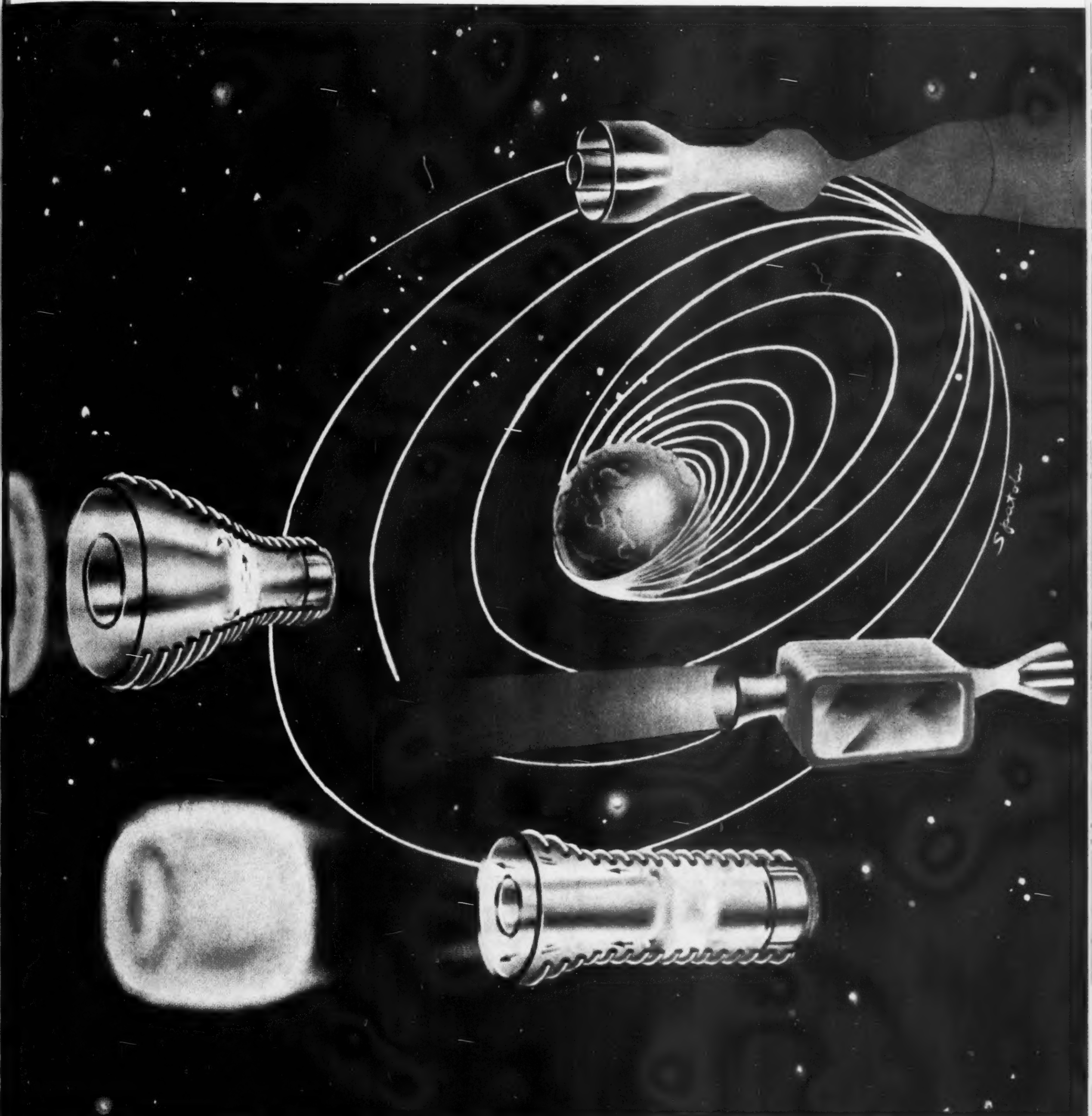
Astronautics

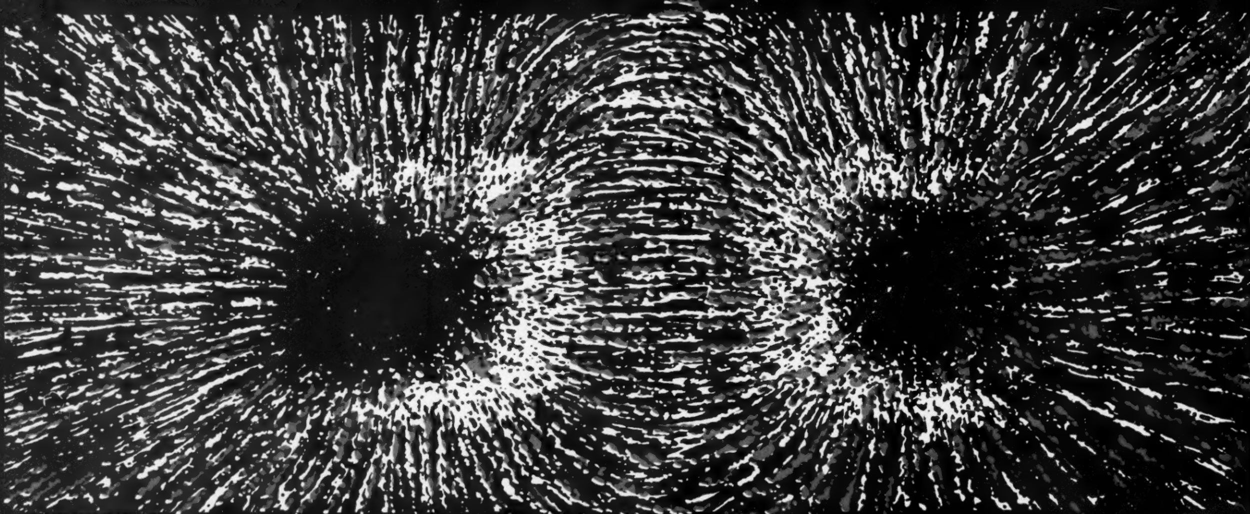
A PUBLICATION OF THE AMERICAN ROCKET SOCIETY

OCTOBER 1959



ADVANCED PROPULSION SYSTEMS

FARADAY the FIELD and FREQUENCY RESONANCE



BURTON BROWNE ADVERTISING

Creative Imagination took Michael Faraday from the experimental discovery of the induction of electricity to the theory of "the field"—foundation of all the new physics including relativity.

Creative imagination at National Co. has taken the known unvarying resonance of the Cesium atom and translated it into a frequency producing instrument with a stability of frequency of 1 part in 10^{11}—this is man's most accurate measurement of time.

The applications and adaptations are many-fold and still largely unexplored.

National Co. is a community of minds and talents that enjoys the challenge and the prestige of success in such advanced fields as multipath transmission, noise reduction, correlation techniques for signal processing, Tropospheric scatter systems, Ionospheric scatter systems, molecular beam techniques, long range microwave transmission, and missile check-out equipment using microwave and digital techniques.

National Co. has grown with the Tradition of New England electronics. Your needs and problems receive exceptional attention at National Co. because, here, *creativity is required, recognized and rewarded.*

Write or phone

tuned to tomorrow **National** ®

National Company, Inc., Malden, Mass.

MANUFACTURERS OF MATERIEL AND EQUIPMENT FOR U.S. DEFENSE

Astronautics

A PUBLICATION OF THE AMERICAN ROCKET SOCIETY, INC.

October 1959 volume 4 number 10

EDITORIAL

ADVANCED PROPULSION

DEPARTMENTS

Print run this issue: 20,923

ASTRONAUTICS is published monthly by the American Rocket Society, Inc., and the American Interplanetary Society at 20th & Northampton Sts., Easton, Pa., U.S.A. Editorial offices: 500 Fifth Ave., New York 36, N. Y. Price $9.00 a year; $9.50 for foreign subscriptions; single copies $1.50. Second-class mail privileges authorized at Easton, Pa. This publication is authorized to be mailed at the special rates of postage prescribed by Section 132.122. Notice of change of address should be sent to Secretary, ARS, at least 30 days prior to publication. Opinions expressed herein are the authors' and do not necessarily reflect those of the Editors or of the Society.

It's the Warhead

that makes a missile pay

The tremendous effort that goes into a missile means little unless the warhead functions properly

Man has been trying to produce positive destruction at an exact location for centuries. With help from the vital and complicated systems found in a guided missile warhead, he is coming closer and closer.

Today's warhead system must rely upon highly accurate safing-arming-fuzing devices to guarantee detonation when and where desired. The degree of sophistication in this system is determined by the specific mission. To date there are six programmed missions: air to air, air to surface, surface to surface, surface to air, underwater to air to surface and underwater to underwater.

What's in a warhead?

Warhead system performance is always critical. In order that the device be safe, armed and detonate upon delivery, the safing, arming and fuzing functions must perform as one system in perfectly timed sequence.

The *safing* system maintains the warhead in a safe condition during handling, launching and flight until the missile has reached a safe distance away from the launch site and friendly troops. Designed to prevent arming and fuzing operations until the projectile nears the target area, this system must be flexible. Maximum safety can be provided through utilization of components which sense such things as minimum preset altitudes or missile velocity. Honeywell makes accelo switches, baro switches and timers for safing systems.

The *arming* system will examine the flight path of the missile, define range, cross range and preset altitude dimensions. The arming system will then decide, based on data collected, whether to prepare the missile for self destruction or on-target detonation! Honeywell makes inertial instruments, timers, baro switches and temperature switches for use in arming systems.

The *fuzing* system, using ultra-sensitive pressure, proximity, time or acceleration sensors, assures precise detonation when and where desired. The method of fuzing may be air burst, contact burst or air burst with contact burst as a backup. If the mission is to be aborted due to a malfunction of any missile subsystem or component, the warhead may be dudded almost to the time the fuzing process begins. Another possible action is called destruct, which means the warhead will be harmlessly destroyed high in the air. Honeywell makes infrared, baro switch, timer, radar, electrical or piezo electric, mechanical and hydrostatic fuzes for warhead fuzing systems.

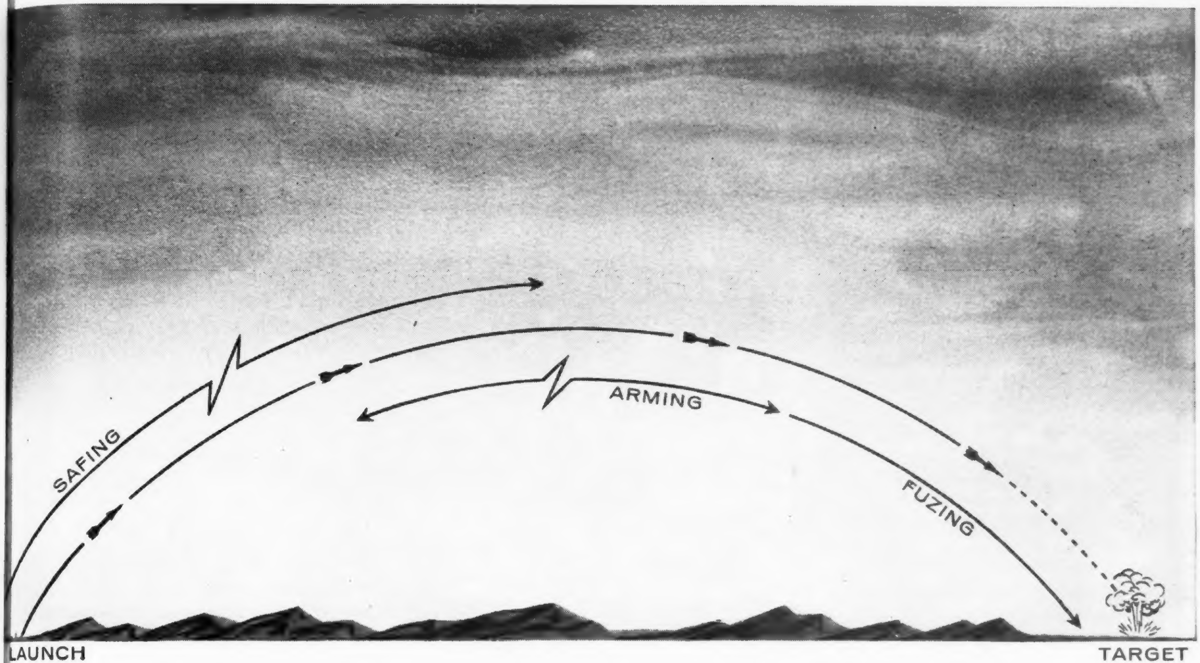
CORPORATE CAPABILITY AND EXPERIENCE

Significant capability stems from a depth of Honeywell experience in inertial systems, gyroscopes, accelerometers, computers, air data systems, ballistic trajectory control systems, horizon scanners, fix takers, pressure and temperature sensors. Honeywell is one of the nation's largest contributors to the entire missile industry as well as to warhead technology. With a notable background in the design, development and production of systems and components, Honeywell is fully qualified for work on all phases of prime missile and space systems management.

For detailed information, call or write Honeywell, Minneapolis 8, Minnesota.

One or more Honeywell warhead systems are on all these missiles:

Redstone Littlejohn Terrier Talos Sidewinder



There are 3 basic systems in a warhead section. *Safing* for storage, launching and flight over friendly territory, *arming* to make warhead capable of exploding, and *fuzing* to assure precise detonation.

GLOSSARY OF WARHEAD TERMINOLOGY

1. Adaption Kit—Those items peculiar to the warhead installation less the warhead; namely, the arming and fuzing systems, power supply and all hardware, adaptors, skins, etc., required by a particular installation.

2. Arming System—That portion of the weapon which derives (originates) the signals required to arm, safe or re-safe the firing system. Will normally consist of accelerometers, arming baros or similar components.

3. Dud Probability—(Warhead Section)—The probability that the warhead fails when launched at a target to produce a nuclear detonation at the desired location.

4. Firing System—That portion of the weapon which, upon signal from the arming system, transforms and stores electrical energy, and upon signal from the fuzing system, discharges this stored electrical energy to detonate the warhead.

5. Fuzing Systems—That portion of the weapon which derives (originates) the signals which discharge the firing system. This system normally consists of such components as pressure, proximity, time or acceleration sensing.

6. Minimum Burst Height—That height above which only an acceptable degree of ground contamination will occur.

7. Premature Probability—The probability that a weapon/warhead explodes before reaching the intended point of detonation in space, including allowable space tolerances.

8. Safe Burst Height—That height above which only an acceptable degree of damage will occur to friendly ground installations.

9. Safing System—That portion of a weapon that integrally contains all the apparatus which, on receipt of proper signals from the arming system or by manual operations, functions so as to place the warhead system in an armed or safe condition.

10. Atomic Warhead Section—That portion of an atomic weapon which consists of the warhead and the adaption kit.

Honeywell

H HONEYWELL Military Products Group

Astro notes

RUSSIAN MOON SHOT

• The Russians hit the moon with a 858-lb instrumented "beer can" Sept. 14 at 2 min and 24 sec after midnight Moscow time. Launched Sept. 12, the Soviet moon probe impacted 35 hr after blastoff within 84 sec of the time predicted by Russian scientists, and, according to their estimates, within 270 mi of the center of the face presented by the moon. There was no report that the impact had been sighted visually, termination of radio signals marking the encounter of probe and moon. The rocket staging and system apparently followed the lines of Mechta. In advance of any proclamation from the U.S.S.R., the U.S. rejected territorial claims to the moon on the basis of a flag planting, which the Russians say the probe has done.

PROJECT MERCURY

• NASA got off to an interesting start with the Mercury capsule flight-test program. While neither of its first two tests worked as planned, both provided illuminating information on the escape and recovery systems of the capsule.

• In the first of its Little Joe shots at Wallops Island, a random electrical signal activated the escape rocket system 20 min before the booster (two Sergeant's and two Recruit's) was to be fired. The malfunction occurred as the battery in the boilerplate capsule was being charged. The escape rocket yanked the capsule some 2000 ft into the air and over the sea, and then jettisoned. The drogue chute popped, but the low battery power was insufficient to eject the main canopy, and the capsule was badly damaged from its plunge into the sea.

• More ambitious was NASA's Big Joe shot at Cape Canaveral, in which a boilerplate model of the 2000-lb capsule (less its escape rocket) was boosted by an Atlas in an attempt to simulate most of the re-entry stresses to be encountered by the capsule and its occupant during return from orbit. The Atlas fired up perfectly, but failed to jettison its outside booster engines at burnout. As a result, the speed, altitude, and range of the shot were substantially less than planned. The capsule did separate from the Atlas, however, reoriented itself in space, and re-entered successfully. All of its recovery mechanisms functioned exactly as planned—the drogue and main canopy, the homing radio beacon, the SOFAR bombs, dye marker, and smoke signal—and the capsule was picked up in "extremely good condition" after floating 7 hr in the sea.

• To Robert Gilruth and his Space Task Group, the Big Joe shot was extremely valuable because it exposed the capsule to a severe type of abort situation. Since it entered the atmosphere more steeply than the shallow (2.5 deg) angle originally planned, it sustained a higher heat pulse and a higher g-load than originally planned. Instead of decelerating at 8–10 g, it reached as much as 15 g, approaching the maximum abort situation visualized by NASA. The fact that it succeeded in this prompted NASA officials to declare that a human astronaut could have survived the identical re-entry if he had taken the ride in a fully instrumented capsule.

• The Big Joe performance was a shot in the arm for GE and B. F. Goodrich, which supplied the ablation heat shield for the blunt end of the capsule. Composed of a phenolic glassbased plastic identical to that used for the ablation nose cone of the Atlas, the GE-Goodrich shield weighs only half as much as the beryllium slab also under consideration for Mercury. NASA is anxious to use the ablation shield because in the event of a descent to earth on the land, an astronaut might be baked alive in a heat sink capsule before he could extricate himself. A water landing is planned, of course, but NASA wants to reduce the risks as far as possible.

SPACE VEHICLES

• ARDC commander Lt. Gen. Bernard Schriever announced that a Dynasoar decision will come this month, and said that selection of a contractor had been delayed because of AF reservations about advanced booster systems proposed by Martin and Boeing, competing team leaders. Boosters will be propulsion systems already developed.

• GE nose cone recovered in an Atlas launch last July was the largest U.S. re-entry vehicle to that time. GE nose cone for a Thor launched that month tested an attitude-control system with a sun tracker and an infrared scanner to locate the "horizon." Recently released photos of the flight sequence of Atlas and Thor vehicles testify to advances being made in attitude control with such sensors, miniature computers, and reaction jets.

• At the Commonwealth Spaceflight Symposium preceding the 10th IAF Congress, Armstrong Whitworth engineers proposed a pyramid-shaped re-entry glider with up to 18-ft-span for use with a British Black Knight and Blue Streak booster system.

• The Delta program may be questioned by Congress, as some members feel it has no place in the national space program. The multistage Douglas rocket, based on a Thor booster, represents an interim vehicle falling between the low-cost solid-propellant Scout and the second generation of NASA space vehicles.

• Using two interim XLR-11 rocket engines, the X-15 made its maiden powered flight high above Edwards AFB, cruising a 100-mi-circumference circle at about 1400 mph. All went well.

• Rocketdyne will make a bid for the X-15 engine program. Its proposal calls for storable liquid propellants in place of the present ammonia-fueled RMI system.

SATELLITES

• Battery troubles may be responsible for malfunctions of Discoverer re-entry capsules, according to ARPA. Both Discoverer's V and VI successfully orbited, both ejected re-entry capsules—and the rest was silence. ARPA believes the capsules' batteries were so degraded by low temperatures during passage around the night side of the earth that they were unable to produce sufficient current to power the complex sequence of re-entry procedures.

• NASA's Paddlewheel (Explorer VI) performed well during its first month in orbit, despite a failure of one of the paddles to latch in place during the launching. This was blamed on reduced power generation by the solar cells (1 amp, falling to 0.8 against a nominal output

of 1.2 amp) during the first weeks of the satellite's life. Interrogation of the satellite's main uhf transmitter, drawing 40 watts, was suspended from Aug. 24–29 to avoid too great a discharge of its nickel-cadmium battery. In late August, however, the satellite's orbit precessed to an angle more favorable for the solar cells, and since then the data has come in regularly.

• NASA's refusal to disclose the frequency of Paddlewheel's uhf transmitter appears somewhat odd in the light of a paper published by an STL scientist, who gave the transmission frequency as 378 mc, with the command receiver operating at 401.6 mc.

• The Army displayed a full-size model of the 475-lb Courier communications satellite, scheduled for launching next year.

• ARPA's Project Suzano for evaluating the need for rendezvous platform satellites must produce a technical decision soon, according to the House Committee on Science and Astronautics.

• East and West agreed at Geneva on the design of a satellite monitoring network to detect upper-atmosphere atomic bomb blasts.

• NASA and ONR set in motion plans for a geodetic satellite to be launched in spring of 1961 with the award of a preliminary design contract for a flashing-light system to Edgerton, Germeshausen, and Grier Inc. The flashing system will make it possible to photograph the satellite with a 5-in.-aperture lens.

• The 11th and last satellite in the Vanguard series was launched into orbit in mid-September, bringing a deservedly happy note to the program's conclusion. The 20-in. Vanguard sphere with its elaborate experiments was topped by a 26-in. tapered tube containing a magnetometer.

• At the same time, a balance of disappointment came with the abort of a Jupiter carrying an extensive bio-pack and the failure of a Thor-Able tipped with the first ARPA Transit navigation satellite to make orbit. The Transit satellite included Navy infrared scanner, solar cell, and ionospheric refraction of radio waves experiments to support the Polaris program.

ADVANCED PROPULSION

• ARPA extended the General Dynamics' feasibility study of controlled nuclear pulse propulsion (Project Orion) for a year with a new million-dollar contract.

• The AF Office of Scientific Research and Avco hold their second joint symposium on advanced propulsion concepts in Boston this month.

• Rosemount Aeronautical Labs of the Univ. of Minnesota has begun the first phase of a major fuel-energy management study for the AF under a $198,500 contract. Study aims at defining optimum use of fuel or propellants in various missions, including spaceflights.

• Bell Aircraft will provide the reaction controls for Project Centaur under a $380,000 contract with Convair-Astronautics.

• ARDC's Arnold Engineering Development Center has planned a complete ground test facility for evaluating ion motors in near-earth missions. Also, a rocket engine generating 15,000 lb thrust was static-fired recently in an Arnold test cell simulating an altitude of 100,000 ft. This and other tests at ARDC have helped solve problems of chuffing and nozzle erosion at high altitudes.

• MIT will conduct research on electrical plasma under a new $500,000 NSF grant. Its plasma research program already covers a half million dollars in related work.

• Alan C. Kolb and his associates at NRL may have made a major advance in controlled-fusion research with a reaction apparently reaching temperatures as high as 15,000,000 C.

• Republic Aviation has expanded its plasma-engine laboratory and begun construction of a second experimental magneto-pinch plasma engine. In one experiment with the first engine, Republic engineers produced a thrust estimated at 8000 lb for an interval of 1 microsec.

SPACE RESEARCH

• A few highlights from the technical sessions of the IAF meeting in London (see page 116): Rosen and Schwenk of NASA gave some thinking on Project Nova (see Sept. 1959 Astronautics, page 20); Kantrowitz of Avco-Everett said his company would be ready to give a full test to its manned re-entry capsule (see July 1959 Astronautics, page 34) within 18 mo, the government willing; Crane of Martin's Nuclear Div. gave the first complete review of the design and potential of Snap III; Chapman of NASA-Ames presented an outstanding analysis of the re-entry corridor for manned spacecraft; Saenger of Germany speculated on the use of shock-plasmas and electron clouds as propulsive jets and weapon "beams"; amplifying their work announced at the IAF meeting last year, Grobner and Cap of Austria exhibited their closed solution of the three-body problem, and illustrated with a numerical example for lunar transit; etc.

• NASA has awarded GE a $500,000 contract to develop a "Nuclear Emulsion" Recovery Vehicle (NERV) for 2000-mi rocket probes into space. Project will involve the development of photographic emulsion packs capable of being rotated within the payload to track paths of high-energy cosmic particles.

• Asked about the imminence of NASA projects to explore the surface of the moon with remotely-controlled mechanical "geologists," a NASA scientist drew laughs with this one: "Hell, we haven't even got a machine which can go out on a parking lot and tell us whether it's made of asphalt or concrete."

• DOD chief of research and development Herbert York recently offered encouragement to some flagging spirits by estimating the U.S. space effort in advance of the Soviet Union's in basic research generally, guidance and control in particular, and satellite utility. U.S. still lags, he pointed out, in heavy-duty propulsion systems.

• NASA launched the first of two Nike-Asp sounding rockets to gather data on upper-atmosphere wind activity by ejecting a sodium-vapor trail. The trail, followed photographically from five stations, extended from 50- to 150-mi altitude. (See Murray Zelikoff's article in July 1959 Astronautics, page 46.)

• The meeting of the American Institute of Biological Sciences at Penn State drew attention to need for considering satellite quarantine stations for space vehicles returning from the moon and planets.

• Experiments with germfree animals raised by Philip Trexler of Notre Dame Univ. are expected to help interpret questions of biological contamination in spaceflights.

• High-frequency noise from very powerful rockets and jet aircraft pose a threat to the health of exposed persons, according to Adam Anthony and his associates of Penn State Univ. He said that experiments with animals showed evidence that long exposure to high-

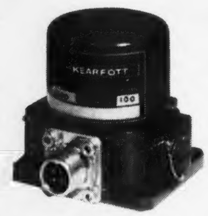
BASIC BUILDING BLOCKS

SERVO SYSTEM COMPONENTS

Synchros—Size 25—20 sec. max. error

- Servo Motors—Frame Sizes 5-25
- Synchros and Resolvers—Frame Sizes 5-25
- Tachometers—Damping, Rate, Integrating
- Transistorized Amplifiers—High Temperature 2.5-16 watts

HYDRAULICS



6100 Series Servo Valve

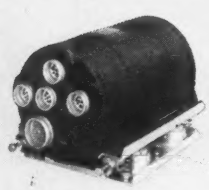
Servo Valves

- Two moving parts
- Anti-clogging—over size orifices, high pressure clearing
- Flow rates—0-5, 0-10 gpm

Systems

For hi-performance hydraulic or pneumatic missile control.

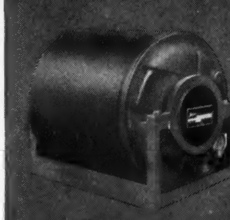
COMPUTERS



Navigational Computer

- Great Circle Course and Navigational
- Inertial Position
- Guidance
- Analog and Digital for Missile Applications

INERTIAL GUIDANCE



25 lb. Inertial Platform

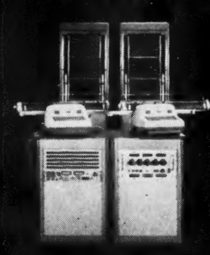
Components include floated gyros, single and two-axis accelerometers, first and second integrators, computers. Complete systems in production for major missile applications feature high accuracy, long-term reliability, light-weight construction.

GYROS

Miniature Floated Gyro

- Rate-floated Integrating; Spring Restrained
- Vertical—Miniature, Self-Contained
- Two Axis Free For Missile Control
- Directional, Conventional and Roll Stabilized
- 3 Gyro, 3 and 4 Gimbal Platforms
- North Seeking Theodolites

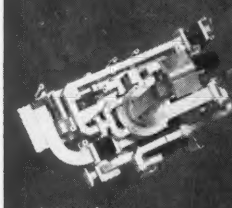
GROUND SUPPORT



Digital Logging System

Completely integrated ground support equipment based on unique Kearfott test equipment modules for analog or digital, manual, semi-automatic or fully automatic testing of components, sub-systems or systems.

MICROWAVE



Antenna Array

- Waveguides, Strip Transmission Lines, Ferrite Components
- Radar rf and Antenna Assemblies
- Transponder Systems, Target Simulators, Test Sets
- Traveling Wave Assemblies

Engineers:

Kearfott offers challenging opportunities in advanced component and system development

Kearfott | A GENERAL PRECISION COMPANY

KEARFOTT COMPANY, INC., LITTLE FALLS, N. J.
A subsidiary of General Precision Equipment Corporation
Sales and Engineering Offices: 1500 Main Avenue, Clifton, N. J.
Midwest Office: 23 W. Calendar Avenue, La Grange, Illinois
South Central Office: 6211 Denton Drive, Dallas, Texas
West Coast Office: 253 N. Vinedo Avenue, Pasadena, California

GPL systems management

equipment for the Federal Aviation Agency

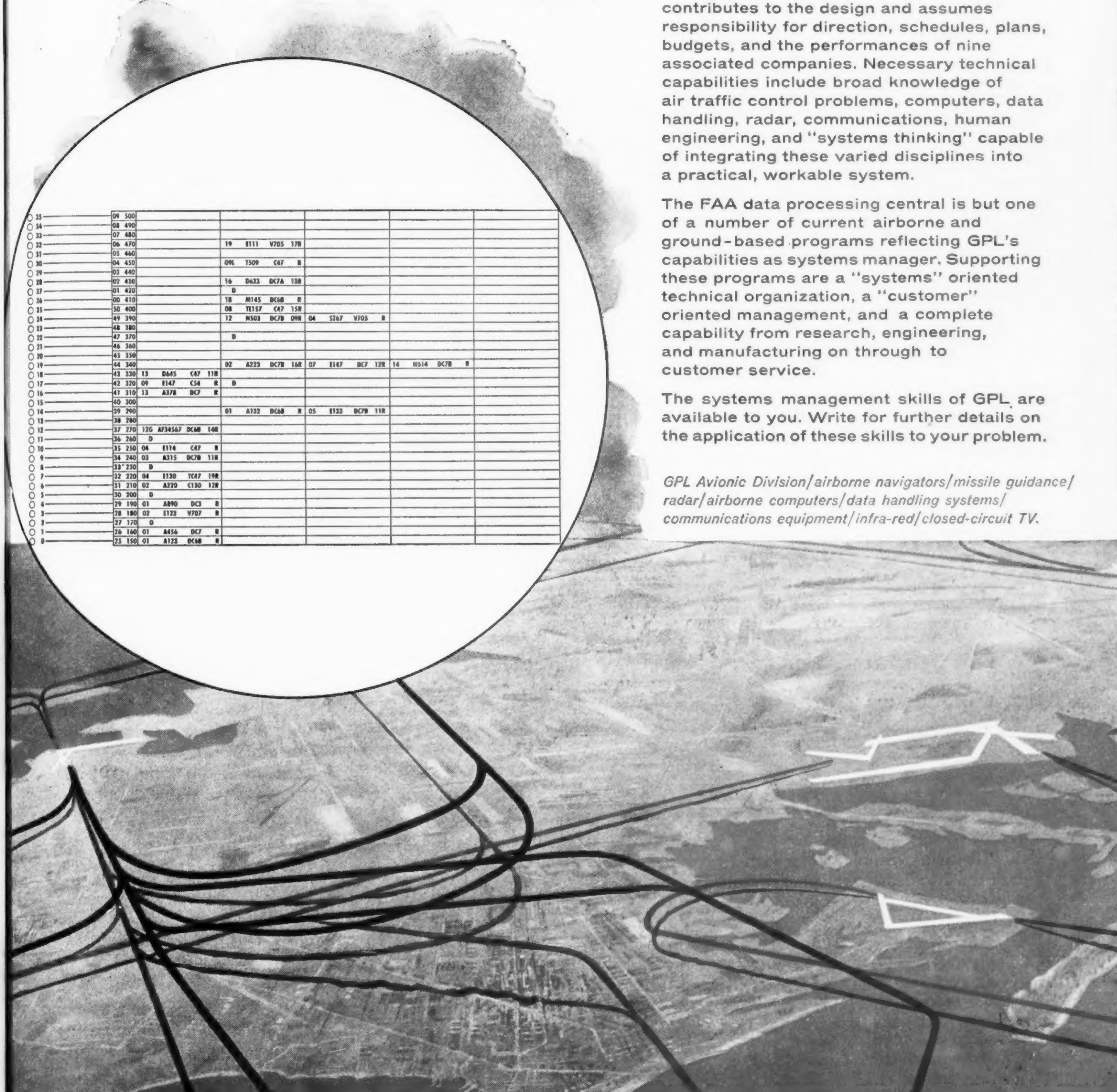
GPL's contracts for the FAA's experimental data processing central—the heart of tomorrow's air traffic control system—point up the diverse talents required of an effective systems manager.

As prime contractor for this FAA Bureau of Research and Development project, GPL contributes to the design and assumes responsibility for direction, schedules, plans, budgets, and the performances of nine associated companies. Necessary technical capabilities include broad knowledge of air traffic control problems, computers, data handling, radar, communications, human engineering, and "systems thinking" capable of integrating these varied disciplines into a practical, workable system.

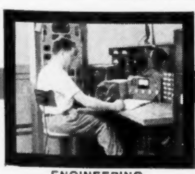
The FAA data processing central is but one of a number of current airborne and ground-based programs reflecting GPL's capabilities as systems manager. Supporting these programs are a "systems" oriented technical organization, a "customer" oriented management, and a complete capability from research, engineering, and manufacturing on through to customer service.

The systems management skills of GPL are available to you. Write for further details on the application of these skills to your problem.

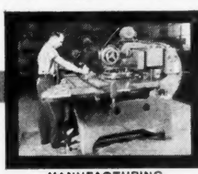
GPL Avionic Division/airborne navigators/missile guidance/ radar/airborne computers/data handling systems/ communications equipment/infra-red/closed-circuit TV.



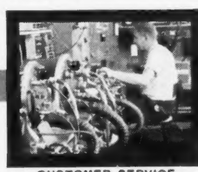
ENGINEERS—GPL achievements have opened a number of challenging research and development opportunities. To be considered for these career positions, send resume of previous experience to Personnel Director.



ENGINEERING



MANUFACTURING



CUSTOMER SERVICE

RESEARCH / FLIGHT TESTING / ENVIRONMENTAL TESTING

GPL | A GENERAL PRECISION COMPANY

GENERAL PRECISION LABORATORY INCORPORATED, Pleasantville, N. Y.

A Subsidiary of General Precision Equipment Corporation

frequency sound could damage important glands.

• A recent NRL Stratoscope flight carried seeds for exposure to cosmic rays and subsequent planting in Republic Aviation's "lunar garden," in study of germination abnormalities, and potential usefulness in spaceship menus.

OPTIMUM TRAJECTORIES

• Optimum trajectories for thrust-limited rockets in a constant gravitational field exhibit at most three maximum-thrust and coasting journey legs. For power-limited rockets, as with an ion motor, optimum trajectories, in particular those for minimum transfer time, require operation at maximum available power with linearly variable acceleration. However, operation at constant acceleration, a condition for most efficient energy conversion (optimum propulsion efficiency), results in transfer times only a few per cent higher than the minimum transfer-time program. Such general solutions against which to judge achievable flight programs are a few of the many ballistic properties of spaceflight that have been derived by George Leitmann of the Univ. of California in studies undertaken for Lockheed Missiles and Space Div.

• Also, the optimum ejection angle for satellites, to conserve booster energy, becomes larger as the specific impulse of upper-stage propulsion stages is increased, according to Dr. Leitmann. This will be noticeably the case when the Centaur stages become available.

NASA

• NASA officials, headed by T. Keith Glennan, visited ABMA last month for a tour of facilities and a briefing on Army space projects, including the Saturn space vehicle. This visit was one of a number Dr. Glennan and his staff are making to groups supporting NASA programs.

• NASA has formed a Bioscience Advisory Committee, headed by Seymour S. Kety, chief of the Laboratory of Clinical Science, National Institute of Mental Health, Bethesda, Md. The Committee will study current U.S. status in space-oriented life-science research and development, outline the scope of present and future problems in bioscience, and recommend NASA programs. Clark T. Randt, NASA chief scientist for Space Medical Research, will be executive secretary to the Committee.

BUDGET

• Watch for a further shakeout in major military weapons programs, particularly in manned aircraft and allied areas. With its victory last spring over the "big spenders" still fresh, the Administration now feels itself in the most powerful position since Sputnik to cope with military financial demands. Defense Secretary Neil McElroy has said he will try to hold fiscal 1961 spending to this year's estimate of $41 billion, but the Budget Bureau is prodding hard for a cut below that level.

• The cuts that the AF and Navy have already ordered in their programs indicate the trend of the fiscal 1961 budget request to go before Congress next January. The AF wiped out its $100,000,000 investment in the high-energy fuel program for aircraft, canceled the GE J93-5 engine under development to burn the fuel, and reduced its B-58 "buy" from 40 to 32 aircraft. The Navy dropped its P6M SeaMaster jet flying boat after pouring $400,000,000 into the project.

• With the major missile programs like Atlas, Titan, and Polaris spending at an increasingly heavy rate, it is impossible to see the $41-billion line held without further cutbacks and cancellations. Vulnerable areas: The AF's F-108 long-range interceptor and B-70 intercontinental bomber, the Navy's J58 program to develop a 30,000-pound-thrust engine (for which no airframe has yet been selected), the nuclear-powered airplane program, and the air-defense program.

• The AF is by no means reconciled to the abandonment of manned aircraft development programs this early in the missile era. Nevertheless, Washington observers expect that the airmen will have to give up the F-108 as a weapons system this year, though possibly continuing the flight article itself as a Mach 3 testbed for the bomber. The B-70 would be continued, although at a slower rate, as an "insurance premium" against the possibility that the ICBM's do not live up to promise. Boeing's B-52H is expected to remain in production, although at a slower rate. With its projected Hound Dog standoff missile capability, this aircraft will remain a potent weapon well into the missile age.

• The same bleak future appears to be facing the Navy's aircraft development plans. The budgeteers will question the need for a Mach 3 carrier-based aircraft powered by a J58 engine when the Navy is simultaneously developing the long-standoff Eagle air-to-air missile, which will have a range of 50–100 mi. Eagle would give a slow, easily-handled turboprop aircraft an enormous defensive capability, eliminating need for a Mach 3 fighter. In fact, some argue that the Navy doesn't even need Eagle, in view of its already-developed long-range Talos.

• In continental air defense, further cuts are regarded as almost inevitable in the AF's Sage network and Bomarc program and in the Army's Nike-Hercules. Since there is little evidence to show the Russians are seriously building up their manned aircraft capability for strategic bombardment, the top civilian cadre at the Pentagon is losing interest in the vast air-defense program projected some years back. Hence the cuts ordered earlier this year by the "master air defense plan" will probably be followed by others which may restrict coverage to the heavily industrialized areas of the U.S. and ignore the rest of the nation.

• The future of Nike-Zeus is still unclear. As the only palpable hope for countering ICBM's, it is likely to remain a development item. But Army demands for a quick production decision will probably be ignored.

• The Navy's big carrier program is likewise uncertain. Congress voted the Navy $35 million to start buying long-leadtime items for a $380 million nuclear-powered vessel instead of the $260 million oil-fired vessel originally requested.

MISSILES

• The AF announced that it had successfully launched a Minuteman with first-stage propulsion and dummy upper stages from an underground firing complex at Edwards AFB.

• The successful launching of a 28-ft test version of the Polaris missile from the USS Observation Island at sea off Cape Canaveral marked an important step toward the Navy's meeting its commitment to provide an operational weapon by 1960. Also, laboratory testing of the Polaris inertial navigation system has been completed by Autonetics, and a prototype engineering model is now undergoing tests on the USS Compass Island at sea.

• Concerning sub-launched missiles, the Explorer VI and the re-

cent Transit satellite carried instruments to check the theory of Robert A. Helliwell of Stanford Univ. that banana-shaped concentrations of ions exist in near space which have great consequence to the development of very-low-frequency communication systems, and thus to radio communication with submarines.

• GE proposes "hardening" its Atlas radio-inertial guidance antennas to 200 psi. Antennas would be mounted flush with the ground, and covered by massive retractable caps until required for launchings. The GE proposal aims at countering some of the competitive advantages of all-inertial systems. All radio-inertial systems now in use, including the Vandenberg complex, are regarded as "soft" because of the exposed antennas.

• Top defense planners are cool to schemes for converting the three-stage solid-propellant Minuteman ICBM to a mobile system by utilizing railroad-car launching beds. They note that the original attraction of the Minuteman is still valid; i.e., it can be plunked into a hole in the ground and forgotten. They figure that a Minuteman in a silo launcher would cost about $2 million—far less than the peripatetic Minuteman.

• Part of the "tidying up" of Atlas for combat readiness included the first launching of the missile, sans warhead, from Vandenberg AFB on the West Coast. The missile went some 4400 mi, the re-entry body landing near Wake Island.

• The Army demonstrated the versatility of a tactical Jupiter by firing it only 300 mi from Cape Canaveral. The Army also tested the complete Nike-Zeus missile system for the first time at White Sands, with partial success.

• The air-launched ballistic missile program gathered momentum as Aerojet-General won the development subcontract for propulsion and GE Missile and Space Vehicle Div. the subcontract for the re-entry vehicle system. Douglas is prime contractor for the AF.

• The Navy will use Reaction Motors' Guardian series of storable liquid rocket engines in Sparrow III and Bullpup. The AF continued its work with Bullpup (under the name GAM-83A) by awarding Martin-Orlando a $5 million contract for further development.

• A ripple on the Titan program scene was AC Spark Plug's awarding of the development of a lightweight digital computer for the all-inertial guidance system to IBM's Federal Systems Div. (In this connection, see the May 1959 ASTRONAUTICS, page 42).

• Armour Research Foundation has developed a new missile flight safety system for the Army Signal Lab that employs three- or four-pulse signals that cannot become confused with missile command signals.

R&D

• The XLR-99-RM-1 engine for the X-15 performed satisfactorily its first static-firing test at Edwards AFB.

• Aerobee-Hi launchings by AFCRC have demonstrated the feasibility of packaging precision infrared equipment for use under extreme environmental conditions and limited space and power. In one launching, three infrared spectroradiometers with volume less than 300 cu in. and powered by no more than 35 watts were lofted to 120 mi and recovered in shape for re-use.

• Rocketdyne's construction of three test stands that will take more than a 1.5-million-lb thrust each has passed the half-way point at Edwards AFB.

• Francis T. Bacon's hydrogen-oxygen fuel cell was recently demonstrated in a developmental version in England. About 30 in. long and 15 in. in diam, the cell produced 5 kw, but also showed extremely complicated and large associated control gear.

• Minneapolis-Honeywell Regulator Co. has demonstrated the practicality of extremely accurate electrically suspended gyroscopes, and the company will now step up its development program for this kind of gyro and related equipment.

• The National Bureau of Standards educational program on the need for better measurement and test facilities in the missile industry and military establishment is beginning to payoff; e.g., precision calibration laboratories will be in operation at most large AF bases by the end of 1959.

• The miniature cooler developed by McMahon and Gifford of Arthur D. Little Inc., which operates on an helium expansion cycle in a closed system, and employs only one cold moving part, a plastic piston, promises wide application in infrared-homing missiles, solid-state masers, miniaturized computers employing cryotrons, and other low-temperature instruments. A model the size of a flashlight battery (the "MinIRcooler") takes only 3 min to reach −315 F.

MATERIALS

• Working under contract to BuShips, Frank Halden of Stanford Research Institute has demonstrated the soundness of William Shockley's suggestion that it should be possible to grow large, pure silicon carbide crystals from solution in alloy melts. As a consequence, semiconductor devices that can operate at temperature up to 1800 F may soon be practical and economical. Also, W. J. Choyke and L. Patrick of Westinghouse's research laboratories have found that a silicon carbide surface can emit electrons directly and continuously. Semiconducting silicon carbide with a *p-n* junction may thus rate as an excellent emitter for vacuum tubes.

• National Research Corp. will study tantalum and tantalum-tungsten alloys for use in nozzles and other solid rocket components under a new BuOrd contract. NRC will test in particular the effects of minor constituents in these metals and alloys and the advantages of carbide coatings on them. Also for BuOrd, NRC will expand its work on very fine aluminum powder for a variety of possible applications.

• Alloyd Research Corp., under contract to BuAer, will design and construct equipment for producing high-purity batches of metals of importance to the missile and space program, such as molybdenum, tungsten, tantalum, and chromium.

• Supported by the AF and the Steel Foundation, Caltech will study the behavior of metals such as titanium and molybdenum up to their melting points with a unique high-temperature x-ray spectrometer which can measure distances with an accuracy of 4 trillionths of an inch.

COSPAR

• COSPAR will hold a Spaceflight Symposium in Nice, France, Jan. 11–16, together with a plenary session. The Symposium will discuss scientific results from the IGY rocket and satellite program. It is not yet known whether the Russian's will participate in the Symposium.

Spencer Laboratory is named for Raytheon's Senior Vice-President, Percy L. Spencer, a pioneer in tube development.

Spencer Laboratory, the newest and most modern research and development laboratory for the design of all types of microwave tubes, has been put into operation at Burlington, Massachusetts by Raytheon.

More than 1,000 personnel are developing new tubes, from tiny missile klystrons to super-power tubes with power levels far exceeding any now in existence.

RAYTHEON COMPANY, WALTHAM, MASS. RAYTHEON

EXCELLENCE IN ELECTRONICS

For the record

The month's news in review

Aug. 2—Army unveils DIGICOM, new robot switching system for battlefield communications.

Aug. 3—NASA announces plans to launch Mercury space capsule next month in re-entry test.

—Senate votes NASA requested $530,000,000 budget, rejecting House cut.

—Rep. Victor L. Anfuso (D., Bklyn), member of House Science and Astronautics Committee, offers bill for student space cadet corps.

Aug. *6*—Polaris test-flight fails.

Aug. 7—NASA successfully orbits 142-lb Explorer VI paddlewheel satellite.

—Navy reveals new radar system, Project Tepee, which would give earlier warning of missile attack than present systems.

—AF meteorological rocket launches weather balloon, Robin, at 50 mi altitude.

Aug. *8*—Navy announces Project Tepee will try to monitor Explorer VI.

Aug. 10—AF cancels $100,000,000 boron-based fuel development program.

—AF says Thor-Able nose cone containing two letters was recovered after 5000-mi trip last May.

Aug. 11—AF successfully fires Atlas.

—DOD drops boron-based-fuel R&D program.

Aug. 12—Army announces development of universal automatic pilot.

—AF Bomarc-B successfully test-fired.

Aug. 13—AF launches Discoverer V into polar orbit, fails to recover 300-lb instrument capsule.

Aug. 15—Univ. of California selects Lassen National Forest site for its $500,000 radio astronomy lab.

Aug. 17—NASA sends aloft Nike-Asp research rocket trailing sodium vapor up to 150 mi altitude.

—NRL scientists believe they may have created a controlled thermonuclear, or fusion, reaction.

—House Space Committee probes government's cancellation of high-energy fuel program.

Aug. 19—AF launches Discoverer VI into orbit, fails to recover instrument capsule.

Aug. 20—AF ARDC launches piloted F-100 from atomic shelter with X-34 solid rocket motor.

Aug. 21—NASA Mercury escape mechanism fires prematurely in first test, leaving main booster on pad.

—NASA sets up Biosciences Advisory Committee.

—Navy cancels jet seaplane development program after spending $400,000,000.

—U.K. reveals development of hydrogen-oxygen fuel cell producing 5 kw.

Aug. 23—U.K. announces adoption of Australian Malkara antitank weapon by British Army.

Aug. 24—AF fires Atlas-C 5000 mi, recovers data capsule with movies of earth from 700 mi altitude.

Aug. 25—Polaris test marred by malfunction in second-stage separation.

—President Eisenhower signs bill creating National Medal of Science, Presidential award to scientists of outstanding achievement selected by NAS.

Aug. 26—Army successfully fires Jupiter over minimum 300-mi-range.

Aug. 27—Navy successful in first firing of Polaris from the ship Observation Island at sea.

—Army fails in first attempt to test-fire Nike-Zeus.

—Government sources hint at another U.S. lunar shot between Oct. 2–4.

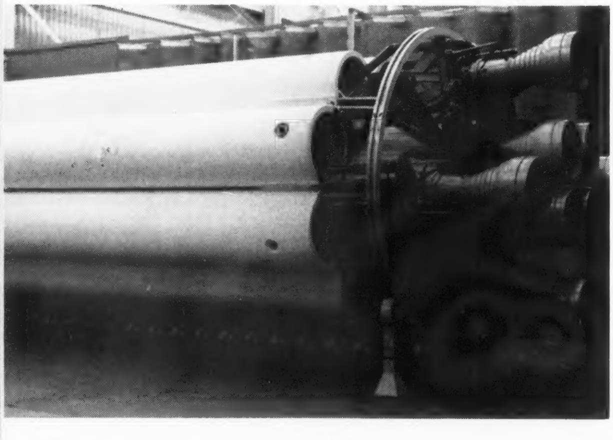
—Woomera tracking station says it has photographed Explorer VI at a distance of 14,000 mi.

Aug. 28—DOD initiates Notus program, calling for use of artificial satellites in polar orbit as radio relay stations.

Aug. 29—Navy technician withstands record 31 g in centrifuge at AMAL, Johnsville, Pa.

Aug. 31—International Academy of Astronautics is urged at opening session of 10th IAF Congress.

—AF announces that camera in nose cone of Atlas fired Aug. 24 photographed one-sixth of earth's surface.



Saturn Booster Model

The eight-engine, 1.5-million-lb-thrust booster assembly for the Saturn space vehicle, under development by ABMA for ARPA, looks like this in quarter-scale model. Full-scale booster will be 75 ft long and 22 ft in diam.

The mail bag

Kudos for ASTRONAUTICS

Dear Sir:

The April 1959 issue, Part 2, of ASTRONAUTICS contained the article, "Educational Opportunities in Astronautics," a report by Paul E. Sandorff, Chairman, ARS Education Committee.

This article has been extensively used by the Special Committee of the Academic Board of the U.S. Military Academy, of which I am Chairman, as a reference guide in evaluating a coverage of astronautics in our curriculum. It is referred to in the body of our report thus: "We evaluate it as the most complete survey of its kind and accept it as the best existing guide for our study."

We have reproduced the magazine article by photostatic processes and used it as an appendix to our report. Your permission is requested for its use in this manner. It is not intended that it shall be circulated outside official channels.

Your prompt reply will be most appreciated.

L. E. Schick
Colonel, U.S.A.
Professor & Head of Department

Dear Sir:

The highly interesting discussion by Howard A. Wilcox ("Science, Weapons, and Civilization") in your August 1959 issue prompts us to inquire if we could obtain permission for reprint, probably digested somewhat, in *Space Digest* with, of course, full credit to ASTRONAUTICS and the author.

Would you advise me, and also let us know if we may deal directly with you or if it is necessary to deal with Mr. Wilcox also?

WILLIAM LEAVITT
Associate Editor

Thanks for the compliments. Permission granted to both.—Editor

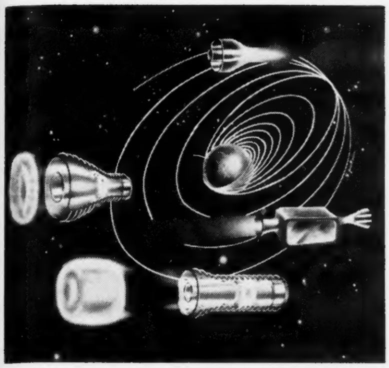
Solid, Not Liquid

The "Missile Market" column by Jerome M. Pustilnik on page 84 of the July 1959 issue of ASTRONAUTICS indicates that the Pogo-Hi target missile is equipped with a liquid propulsion system. This information is incorrect. The Pogo-Hi target missile is currently equipped with Cajun rocket motors, an "off-the-shelf" unit manufactured by Thiokol.

The reliability and low cost of the Cajun rocket motor has enabled Pogo-Hi to become one of the most successful target missiles available today.

We hope this information will be of interest to you. . . .

ARNOLD IRWIN
Head, Propellant Projects Section
Elkton Div.
Thiokol Chemical Corp.



COVER: *Artist Joseph Spatola of Avco-Everett Research Lab provides a graphic illustration for the theme of this issue—Advanced Propulsion Systems. Shown clockwise from the top are four electric thrust devices (see page 31) under study at the lab: Electric arc (plasma) jet, MHD plasma accelerator, MHD shock tube, and MHD rotor.*

Astronautics

OCTOBER 1959

ARS and the World of Today

Today scarcely separates yesterday's obsolete breakthrough from tomorrow's newest triumph. Never in human history has there been such an exponential surge of discovery and invention. Literature and the arts had their renaissance; science emerges uniquely out of the dark ages in continuous increments of enlightenment, the cumulative basis for an ever-expanding frontier of progress. Through research and development, knowledge is translated ever more directly and swiftly into power—the devastating power of atomic explosions, the overwhelming power of atomic diplomacy; the instantaneous, universal reach of electronic communications, the impact of ideas simultaneously transmitted to millions of minds in many languages; the time barriers of travel shortened by aerial transport at sonic speed, making the ends of the earth contemporary, dispelling anachronistic isolation.

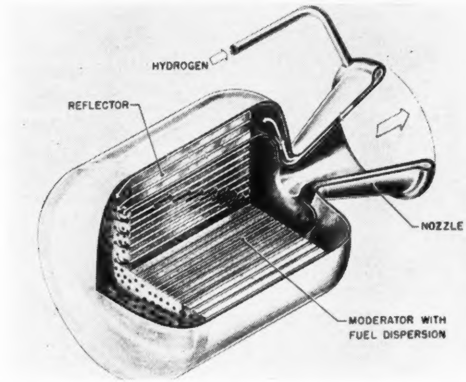
Today's scientists cannot blindly concern themselves with discovery for discovery's sake, abstracting themselves from the consequences of inventions, isolating themselves in esoteric idiom, disdaining communication with the community of mankind. Never has there been more peril implicit in their being misunderstood. Further than that, they have an obligation to inform and to be understood, to accept responsibility toward human society for the control and proper use of power gained from discovery. The legend of the sorcerer's apprentice turning the oceans salty with a runaway magic mill becomes uneasy reality in the potential threats of nuclear fallout.

Today, the basic internal responsibility of ARS for disseminating new information to our membership through the scientific programs arranged by our 22 technical committees, and published periodically in our two journals, has added to it an increasing need to translate information accurately into the vernacular of the lay citizen. His need to know comes from paying the taxes that support the greater part of astronautical and missile research and development, and from the adjustments he must make to its effects on his way of life. Even more imperative is the responsibility to educate coming generations, not only to recruit replacements in a growing frontier of science, but to assure sympathetic support from enlightened citizens, oriented to accept progress.

Ways and means of facing these growing responsibilities invite the best thinking of our members to guide the actions of our Society in meeting our obligations to the World of Today.

—John P. Stapp
President, American Rocket Society

Graphite Solid-Reactor Rocket



Advanced reactor concepts for nuclear propulsion

Each way of skinning the nuclear-rocket cat—solid, liquid, or gaseous phase reactor—challenges engineering science

By Frank E. Rom

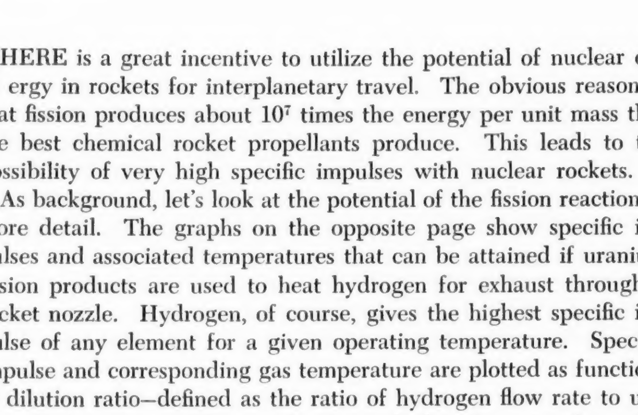
NASA LEWIS RESEARCH CENTER, CLEVELAND, OHIO

Frank E. Rom is the chief of the Nuclear Propulsion Systems Branch of NASA's Lewis Research Center. After receiving an M.S. degree in mechanical engineering from Cornell Univ. in 1948, he joined the staff of the NACA Lewis Flight Propulsion Laboratory as an aeronautical research scientist. In 1950, he was assigned to what is now the Nuclear Reactor Div. to do systems analysis of nuclear-powered aircraft, and subsequently became head of the Systems Analysis Section, conducting analyses of turbojet, turboprop, ramjet, ducted fan, and other cycles for aircraft nuclear propulsion. In 1956, he was appointed to his present position. His work now includes nuclear space propulsion systems, experimental heat transfer, and reactor fuel-element research. He is a member of the ARS Nuclear Propulsion Committee and serves on the Project Rover Coordination Committee.

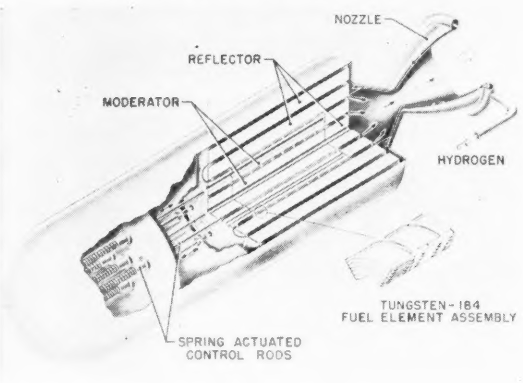
THERE is a great incentive to utilize the potential of nuclear energy in rockets for interplanetary travel. The obvious reason is that fission produces about 10^7 times the energy per unit mass that the best chemical rocket propellants produce. This leads to the possibility of very high specific impulses with nuclear rockets.

As background, let's look at the potential of the fission reaction in more detail. The graphs on the opposite page show specific impulses and associated temperatures that can be attained if uranium fission products are used to heat hydrogen for exhaust through a rocket nozzle. Hydrogen, of course, gives the highest specific impulse of any element for a given operating temperature. Specific impulse and corresponding gas temperature are plotted as functions of dilution ratio—defined as the ratio of hydrogen flow rate to uranium fission rate—and burnup fraction, which is the ratio of uranium fissioned to total uranium used. As the dilution ratio approaches zero, the propellant gas approaches pure fission products; and at this

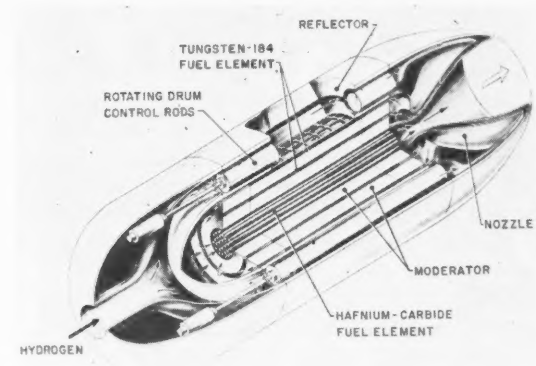
Velocity Requirements for Space Missions



Tungsten-184 Solid-Reactor Rocket



Tungsten-184 and Hafnium Carbide Multi-pass Solid-Reactor Rocket



limit, specific impulse reaches a limiting value of about 10^6 sec. The corresponding temperature of the fission reaction is about 10^{12} F. Actually, complete burnup would not be possible, and specific impulse and temperature would be something less, depending on the burnt fraction of uranium.

Potentially, then, uranium fission can produce specific impulses of the order of hundreds of thousands pounds-force per second per pound-mass of propellant—but at operating temperatures of hundreds of billions of degrees Fahrenheit.

Temperature vs. I_{sp} Compromise

Obviously, some compromise must be made between operating temperature and specific impulse. Reducing operating temperature below the melting point of solid materials gives specific impulses sufficiently greater than those achievable by chemical means to make a nuclear rocket using solid-fuel elements worthwhile. Indeed, any temperature above about 1500 F will produce a specific impulse higher than that attainable with the best high-energy chemical propellants.

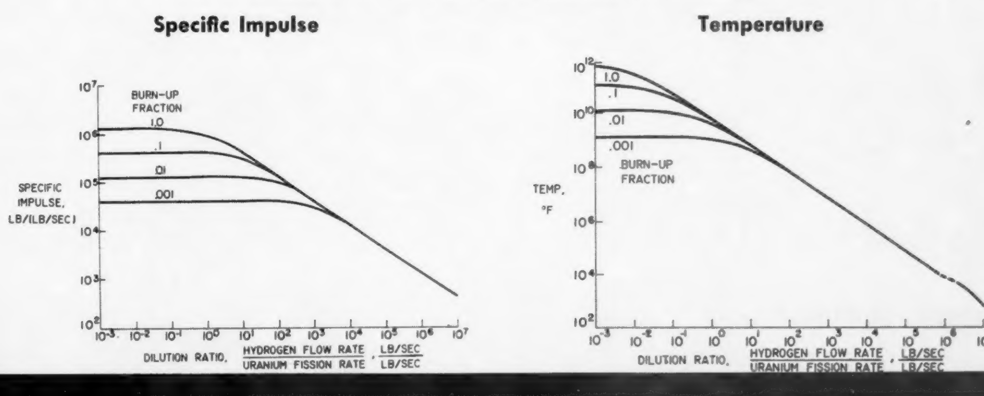
This suggests that the logical first step in nuclear-rocket propulsion should be the attainment of suitable high-temperature solid-fuel-element nuclear reactors. The Los Alamos Scientific Laboratory, working toward this goal, has reported success in the initial tests of the Kiwi-A reactor.

In solid reactors, such as Kiwi-A, fuel elements consist of the fissioning uranium contained in solid materials with high melting points. The working fluid, hydrogen, flows through or over these fuel elements to be heated for expansion through a nozzle.

The melting points of the solid materials that must contain the fissioning uranium determine the maximum operating temperature of the propulsion system. The most refractory materials are the carbides of hafnium and tantalum, which melt at about 7000 F. With this melting-point limit in a solid-element reactor, perhaps a temperature of about 6000 F can be produced in hydrogen gas. Specific impulse would then be about 1200 to 1500 sec.

In other words, even if one were to use the straightforward approach of the solid-fuel-element reactor, specific impulses almost three times as great as the best that can be attained with chemical propellants are possible.

Potential of the Fission Reaction for Rockets



After considering a solid-fuel-element reactor, which is limited by melting points of materials, a natural step might be the use of a molten-fuel reactor through which the working fluid, hydrogen, is bubbled. The maximum temperature would then be limited by the boiling point of the most refractory uranium compounds. For example, uranium carbide, which has a boiling point of approximately 7900 F at a pressure of 1 atm, could produce specific impulses of roughly 1500 to 1800 sec with hydrogen as a working fluid.

A further step would be to consider a uranium compound in the gaseous state as the source of energy for heating hydrogen. The limit in temperature in this case would be either the ability to cool the walls of the chamber surrounding the reactor gas or the uranium density required at reasonable pressures to maintain a chain-reacting mass in a reactor of reasonable dimensions.

To determine the range of application and the benefits to be gained by going from chemical rockets to solid, liquid, or gaseous nuclear rockets, it is necessary to examine the specific impulses required for various space missions. The graph on page 20 presents mass ratio as a function of specific impulse for various space missions. Mass ratio is defined as the ratio of final to initial mass of the rocket vehicle.

The missions shown in the graph are given in terms of velocity increment (Δv) in miles per second (mps). A velocity increment of 2 mps corresponds to one-way interplanetary probe flights started from orbit about the earth. Minimum-energy, orbit-to-orbit, round-trip flight to Mars of 973-day duration, and also earth-takeoff interplanetary probes, are characterized by a Δv of 7 mps. A velocity increment of 16 mps is required for Earth-Mars orbit-to-orbit flight with a 30-day wait at Mars and a total trip time of 1 yr. A velocity increment of 30 mps is needed to reduce the Mars trip to 3 mo. A velocity of 100 mps corresponds to velocity increments required to explore the entire solar system.

If a mass ratio of 0.03 is considered reasonable, then specific impulses of at least 100, 300, 750, 1400, and 4600 sec are required for velocity increments of 2, 7, 16, 30, and 100 mps, respectively. Chemical rockets are limited to the first two missions, because the highest chemical specific impulse is less than 500 sec. Solid-fuel-element reactors can handle velocity increments up to 30 mps. The range of 30 mps and beyond requires liquid- or gaseous-phase reactors.

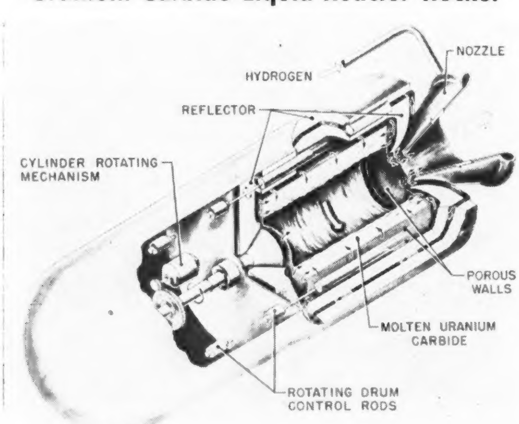
Reactor Possibilities

What might the various reactors—solid, liquid, and gaseous phase—look like? What might they be made of? What performance might be expected of them? In attempting to answer these questions, use will be made of basic ideas suggested by many people for conceptual design.

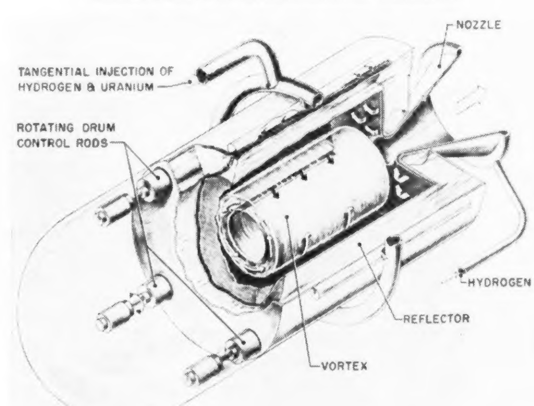
Solid-fuel-element reactors enclose the fissionable matter in solid materials. The fission products collide internally with the atoms of the fuel-element material and cause their kinetic energy to be degraded to random thermal energy. This energy is in turn transmitted via heat transfer from the fuel elements to the hydrogen propellant flowing through the reactor.

Materials to contain the fissioning matter are of major concern in solid-reactor engineering. Materials typically considered have been graphite, metals, and ceramics. Graphite, or carbon, is the first material one would consider for a high-temperature nuclear-rocket reactor because of its well-known high-temperature properties, availability, and ability to moderate neutrons. Carbon or graphite was suggested as a reactor ma- (CONTINUED ON PAGE 46)

Uranium Carbide Liquid-Reactor Rocket



Gaseous-Vortex-Reactor Rocket



Gaseous-core nuclear rockets

Conceivable in many forms, they seem at present mostly a field for speculation, but experiments in progress may bring them close to reality

By Jerry Grey

PRINCETON UNIV., PRINCETON, N.J.

AN EXPLORATION of the methods leading to more efficient propulsion-system applications of the enormous energy available from nuclear reactions leads directly to the concept of a gaseous-core rocket. A gaseous-core nuclear reactor can be defined as one in which the nuclear fuel exists in the gaseous (or plasma) state. Since the technology of gaseous nuclear fuels has not yet been attempted experimentally, the gaseous-core nuclear reactor is at present only a concept. Thus, although theoretical feasibility has already been demonstrated for some gaseous-core systems, several of the practical problems may still prove prohibitive.

The basic justification for a gaseous-core nuclear rocket, as is usual with any radically new system, is that significant performance gains may be realized. Consider the well-known dependence of rocket vehicle performance on propellant exhaust velocity. All other things being equal, burnout velocity, and therefore vehicle range, is directly proportional to propellant exhaust velocity. In a thermodynamic system, this means range is proportional to the square root of the propellant "chamber" temperature. Now, in a "conventional" nuclear-rocket reactor the propellant is heated by contact with the hot reactor structure containing the fissionable fuel, limiting the maximum temperature to that at which the structural material can maintain its shape. Since the highest material *melting points* known are around 6500 F, the likelihood of propellant temperatures exceeding, or even reaching, 6000 F is rather remote.

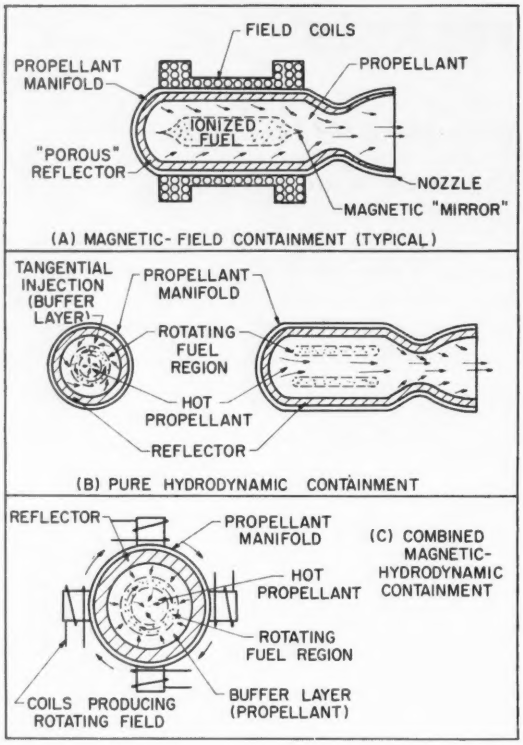
Gaseous Core the "Fix"

The obvious "fix" is to remove the solid fuel-carrying structure, allow the nuclear fuel to become gaseous, and mix it with, or actually allow it to become, the propellant. By using a cooled container, very high gas temperatures may then be realized. This principle is in itself not at all new or different. The conventional chemical rocket, often built of a cooled dural alloy which melts at around 1400 F, utilizes flame temperatures which for some propellants may approach 9000 F.

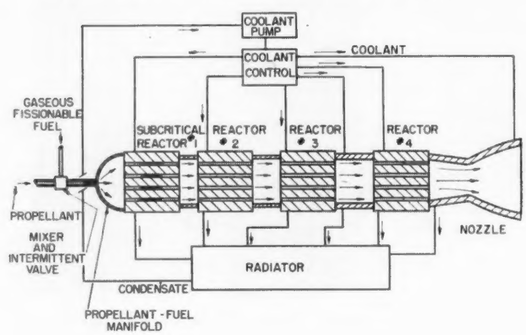
The principal advantage of the gaseous-core system, then, is its higher operating temperatures, resulting in higher specific impulse. (The thrust level for some concepts is comparable with that of the conventional nuclear rocket.) The disadvantages of gaseous-core systems, unfortunately, appear to be quite severe. Although they vary somewhat among the several concepts, the two basic technical

Jerry Grey is an assistant professor of aeronautical engineering at Princeton Univ., in charge of high-temperature plasma transport studies there, and a consultant to a number of companies on propulsion systems, gas dynamics, and instrumentation. He received a B.Me. from Cornell Univ. in 1947, an M.S. in engineering physics from Cornell in 1949, and a Ph.D. in aeronautical engineering from the California Institute of Technology in 1952. He has been a member of the technical staff of Bell Labs, an instructor in thermodynamics at Cornell, a development engineer at Fairchild Engine, a hypersonic aerodynamicist with GALCIT, and a senior engineer on ramjets for Marquardt.

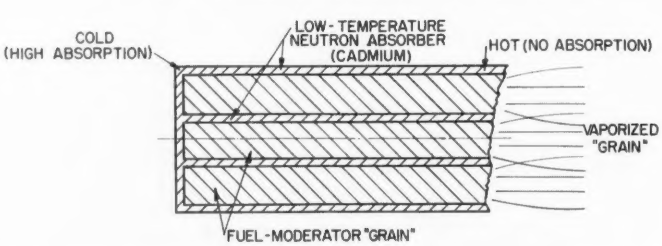
Fissionable-Fuel Containment in Cavity Reactors



Hybrid Solid-Gaseous Rocket System



Solid-Propellant, or Fizzler, Rocket System



difficulties generally break down to the following:

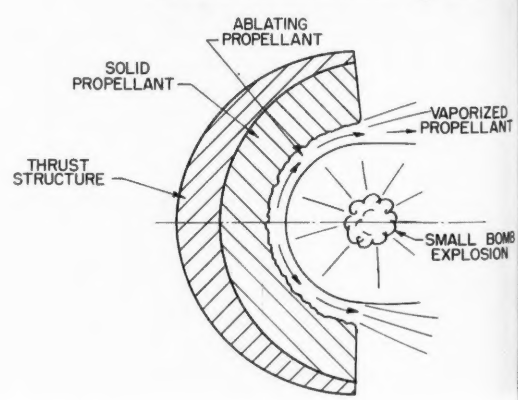
1. Limitation of attainable temperatures by wall cooling requirements, which are likely to result primarily from the enormously high thermal radiation level.
2. Economical maintenance of the conditions necessary for the controlled nuclear reaction, in terms of either weight or cost.

A third serious consideration, although not important to basic feasibility, is the amount of radioactive material expelled. Although this is actually far less than that produced by the smallest of atomic bombs, it could form the basis for political controversy. Finally, there is the environmental requirement for shielding, and the operational problems of control, instrumentation, testing, etc. These, unfortunately, will be difficult to assess until some experimental experience has been accumulated.

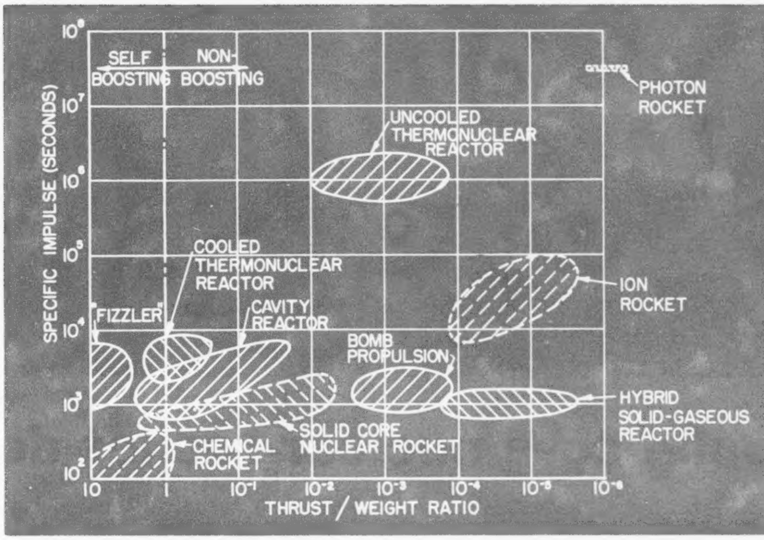
There are almost any number of conceivable configurations for gaseous-core rockets. Although all have higher performance than the solid-core reactors, some may produce better than 1-g accelerations, while others have only small thrust-to-weight ratios. The few examples to be discussed might be sketched as follows:

1. A more or less homogeneous mixture of propellant and fissionable fuel gases—usually called a "cavity reactor" because of the need for a dense neutron reflector surrounding the gaseous region.
2. A series of barely subcritical solid-fission reactors through which there passes intermittently a gaseous mixture of propellant and sufficient fissionable fuel to produce criticality.
3. A "solid-propellant" rocket utilizing fission-

Nuclear-Bomb Rocket System



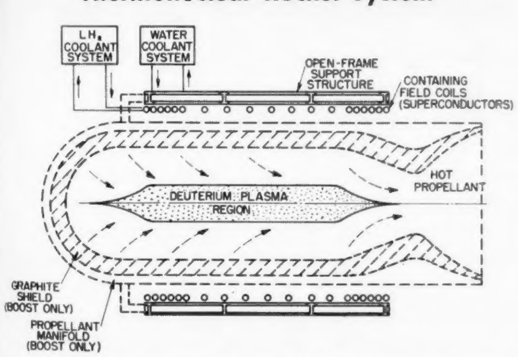
Performance of Gaseous-Core Propulsion Systems



able material mixed in a solid "grain" with a moderating propellant, and "ignited" by removal of a control rod; often called a "fizzler".

4. A series of small fission bomb explosions, the impacts in the forward direction being absorbed preferably by a good propellant material which is thereby itself vaporized and exhausted (Project Orion).
5. A fusion-powered (thermonuclear) reactor used to heat a separate propellant (somewhat similar to the fission-powered cavity reactor).
6. A thermonuclear-powered reactor using fusion products themselves as propellant, together with the hot fuel plasma.

Thermonuclear Rocket System



Note: Propellant system, including shield, tankage, and nozzle, shown within dashed lines, is jettisoned after boost.

Let's look at each of these schemes in more detail.

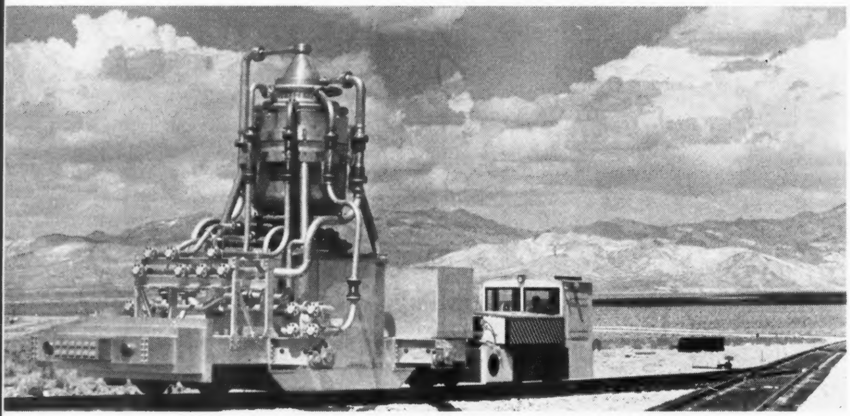
A *uniform* critical mixture of gaseous fissionable fuel and propellant is impractical from a cost viewpoint. Shepherd and Cleaver pointed this out as early as 1951, showing that even the most elemental of space missions would require the expenditure of prodigious sums for the uranium expelled from the nozzle. Some preferential retention of the fissionable fuel is thus essential.

Two Methods for Retaining Fuel

Fortunately, the nature of the system provides two obvious methods for accomplishing this retention. The first of these depends on the basic high-temperature requirement for high performance: At any temperature sufficiently high to be of interest, the heavy fuel atoms will become almost completely ionized, and may be retained by a "magnetic bottle" of some sort. A low-molecular-weight propellant is then selected which will *not* be appreciably ionized at the desired operating pressure and temperature, and therefore may flow unimpeded out of the nozzle to produce thrust. Because of its high ionization potential, helium would be a good propellant for this application.

The second method for achieving fuel retention is based on the fact that fissionable fuels have very high atomic mass numbers, whereas the best-performing propellant gases are those with the lowest mass numbers. Thus there is the possibility of utilizing some sort of hydrodynamic "centrifugal separator."

A third mechanism, utilizing both of these properties of the fuel-propel- (CONTINUED ON PAGE 110)



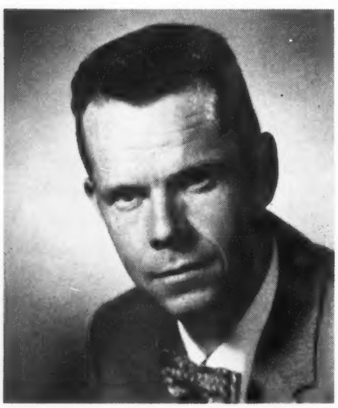
The state of the art of solid-core nuclear rockets took a big step forward recently with the successful testing of the Kiwi-A reactor, shown here as a mockup on a test cart at the AEC Nevada Proving Ground.

Solid-core nuclear-rocket design

Deriving the greatest performance from a solid-core nuclear rocket requires intricate engineering of fissionable material, flow system, structure, controls, and many other design aspects

By Franklin P. Durham

LOS ALAMOS SCIENTIFIC LABORATORY, LOS ALAMOS, N.M.



Franklin P. Durham is group leader in charge of engineering design in the Los Alamos Scientific Laboratory's nuclear-rocket propulsion program. An engineering graduate of the Univ. of Colorado, where he received B.S. (M.E.), M.S. (M.E.), and A.E. degrees, his propulsion experience, dating back to 1943, includes reciprocating engines, turbojets, and rockets. He was a professor and head of the Aeronautical Engineering Dept. at the Univ. of Colorado before joining the Los Alamos Laboratory in 1957, and is the author of college textbooks on jet powerplants and thermodynamics.

SOLID-core nuclear reactors, wherein a lightweight propellant such as hydrogen is heated to a high temperature to give specific impulses of about 800 sec, have long been considered for rocket propulsion. The virtues of such high specific impulse are well known for spaceflight, and have led to the current nuclear-rocket propulsion program at Los Alamos Scientific Laboratory which began in 1955. The first phase of this program has been completed with the recent successful test of the Kiwi-A experimental reactor.

Many materials, such as tungsten, molybdenum, tantalum, graphite and various carbides, maintain structural integrity up to temperatures sufficient to allow high specific impulse. However, the scientific and engineering problems associated with incorporating such materials in a useful propulsion reactor are of considerable magnitude.

While nuclear reactors offer the possibility of specific impulses approximately twice as great as those of the best chemical systems, they have several potential disadvantages that must be considered and minimized where possible. These are reactor weight, problems involved in neutronic startup and control, and the intense radiation field during power operation. Further, the inherent reliability of such systems is an unknown quantity, although assumptions regarding reliability must be made in choosing one reactor design over another.

To gain some insight into solid nuclear rockets, let's look at design considerations of turbulent-flow solid-core heat-exchange reactors. A typical reactor is shown schematically on the opposite page. The components of such a reactor are:

1. Core heat exchanger, consisting of fuel elements, neutron moderator, and structure.
2. Neutron reflector surrounding the core.
3. Neutron control rods and actuating mechanism.
4. Regeneratively cooled nozzle and pressure shell.

The fissioning material is assumed to be uranium-235. Common reflector materials are beryllium, graphite, deuterium, and water.

Neglecting chemical dissociation and recombination effects, the vacuum specific impulse of a propellant is given by the approximate relation, $I_{sp} = C\sqrt{T_t/m}$, where C is a constant for a given nozzle area ratio and gas specific heat ratio, T_t is the propellant stagnation temperature, and m is the propellant molecular weight. For flight within the atmosphere, an additional variable back-pressure correction factor, less than unity, must be applied to this equation.

The choice of hydrogen as a working fluid assures the lightest possible molecular weight propellant. While other propellants, such as ammonia or methane, might be desirable from the point of view of logistics and handling, the choice of any propellant other than hydrogen reduces one of the primary attributes of nuclear propulsion –high specific impulse. Reactor fuel-element and structural materials must not only have desirable high-temperature physical properties, but must also be chemically compatible with the propellant over its full temperature range.

Having chosen a propellant and a reactor structural material, the designer is faced with the problem of maximizing the average propellant exit stagnation temperature for a given maximum allowable local material temperature. Obtaining a uniform exit gas temperature may be approached in either of two ways:

1. Radial variation of uranium concentration to obtain uniform radial fission distribution with uniform flow passage dimensions.
2. Radial variation of the number of flow passages or hydraulic diameter with uniform uranium concentration.

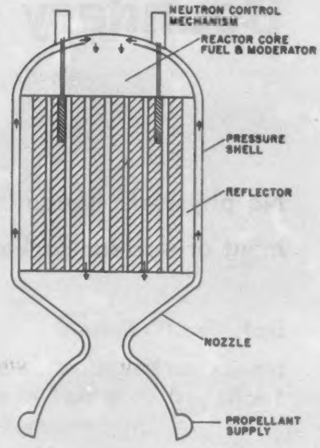
In general, if thermal stress in the fuel elements is limiting, the first of the two methods will yield the smallest reactor. If, on the other hand, maximum uranium loading in the fuel elements is limiting, the second of the two methods will give the smallest reactor.

Heat Exchanger Requirements

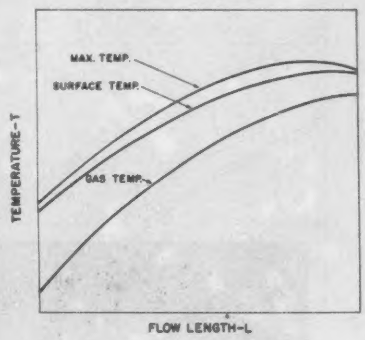
In addition to the uniform radial temperature problem, the heat exchanger must have sufficient surface area and adequate axial power distribution to heat the propellant to a temperature near the maximum allowable surface temperature. In general, a flow passage length-to-hydraulic diameter ratio in excess of 300 is required, and the axial fission distribution should be peaked forward of the center of the reactor. A simple method of obtaining some degree of forward peaking is to provide a neutron reflector at the inlet end of the core while leaving the exit end unreflected. Additional forward peaking may be obtained by axial variation of the uranium loading concentration.

The lightest possible weight for given reactor power is a requirement that distinguishes propulsion reactors from commercial electrical power reactors. The term "power density" is used as a measure of how successfully this requirement (CONTINUED ON PAGE 102)

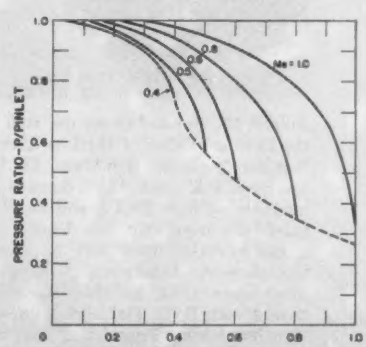
Solid-Nuclear-Rocket Schematic



Typical Axial Temperature Distributions



Effect of Exit Mach Number on Pressure for Constant Flow Rate and Heat Input



Boundary conditions for nuclear propulsion

No physical phenomena yet discovered will prevent development of nuclear rockets for exploring our whole solar system

By Robert W. Bussard

LOS ALAMOS SCIENTIFIC LABORATORY, LOS ALAMOS, N.M.

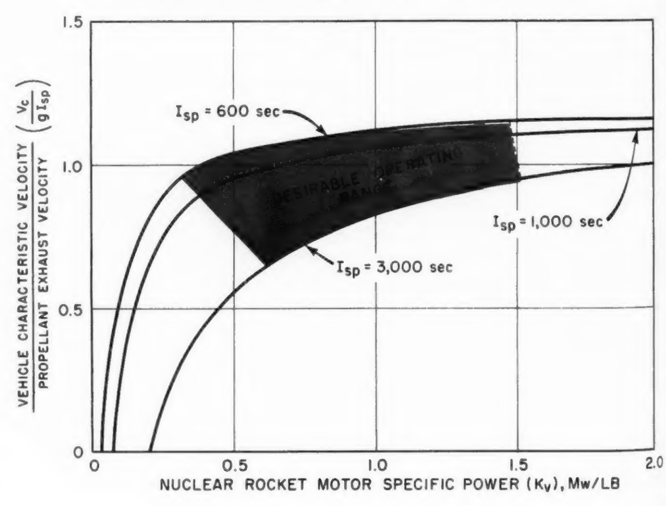
IT HAS often been noted that since nuclear bond energies are the order of 10^7 times greater than chemical bond energies, very great gains in performance are theoretically allowed by the application of nuclear energy to rocket propulsion. Whether or not such gains are actually achieved depends upon how well the engineering problems of the various proposed methods of application are solved, as finally proved by experiment. However, it is not necessary initially to consider the detailed problems of specific designs in trying to assess the proper role of nuclear energy for rocket propulsion systems of the future.

Rather, we should first ask if there are rocket vehicle mission requirements which naturally define areas of interest for the most *reasonable* application of nuclear energy to rocket propulsion. To answer this question, we must examine the relations between nuclear propulsion system and rocket vehicle performance in a rather general way and for a wide range of vehicle missions.

Let us limit our interest to ground-launched nuclear rockets, and

Robert W. Bussard is on the staff of the Division Office of the Los Alamos Nuclear Propulsion Division. He has received B.S. and M.S. degrees in engineering from UCLA and an M.A. in physics from Princeton Univ. Engaged in rocket work since 1949, and in high-power-density reactor development since 1952, he also has co-authored with R. D. DeLauer the book, "Nuclear Rocket Propulsion," and was lecturer this year in the UCLA summer course on this subject.

Nuclear-Powered Spacecraft Performance



assess the propulsion-system performance conditions which must be met for the attainment of *reasonable* vehicles of this type for use in solar system missions.

Further, let us define *reasonable* performance as follows: Single-stage rocket vehicles capable of carrying payloads of 10 to 30 per cent of gross mass. Few of us would argue that this is not good enough. (Explorer VI was approximately 0.2 per cent of gross vehicle mass at takeoff.)

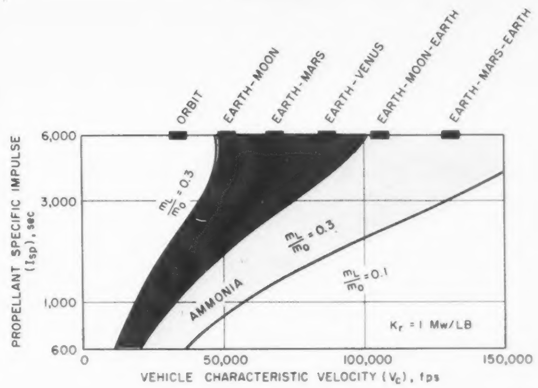
The components of chief interest in analyzing the rocket-vehicle performance are then the nuclear-rocket motor (m_r), the propellant pumping plant (m_{pe}), the propellant itself (m_p), propellant tank structure (m_t), and deadload (m_L), defined to include all remaining equipment. It is not necessary to specify the type of motor or propellant at this point, nor even the source of nuclear energy. But for convenience we shall speak of a fission source, as it is presently the only controllable process of the three possible—fission, fusion, and radioisotope decay.

The mass of all of these basic components can be related either to propulsion system power or to total energy output during powered flight. Since the power required is proportional to the thrust, and hence to the gross vehicle mass (m_o), and the energy is proportional to propellant mass, it is possible to write the gross vehicle mass as the sum of a number of components each dependent either upon propellant or gross mass. This gives us one relation between m_o, m_p, and m_L, as follows:

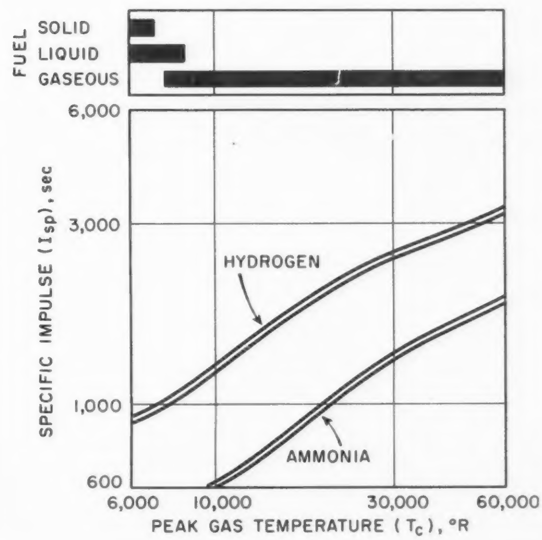
$$m_o = A_t \frac{m_p}{\rho_p} + A_{pe} \frac{m_o}{\rho_p I_{sp}} + A_r \frac{m_o I_{sp}}{K_r} + m_p + m_L$$

(CONTINUED ON PAGE 119)

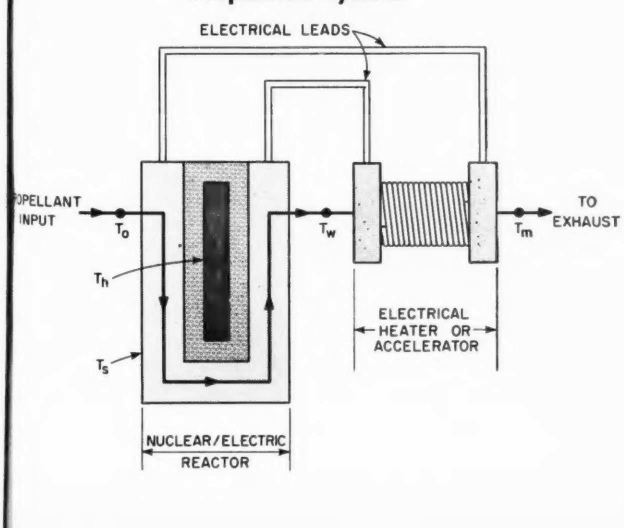
Performance in Terms of Propellant and Mission



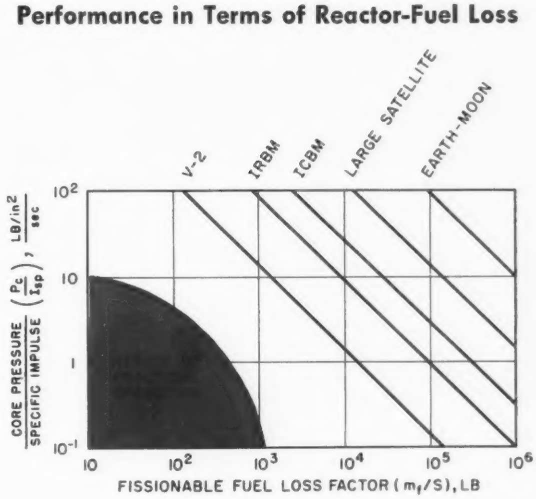
Performance in Terms of Propellant Temperature



Regeneratively-Cooled Nuclear/Electric Propulsion System



Performance in Terms of Reactor-Fuel Loss



Applications of magnetofluidmechanics

Starting out as an "ideal intellectual playground for aerodynamicists and mathematicians," it now promises many practical applications in three different areas—flow modification, containment, and propulsion

By Theodore von Karman

AGARD, PARIS, FRANCE

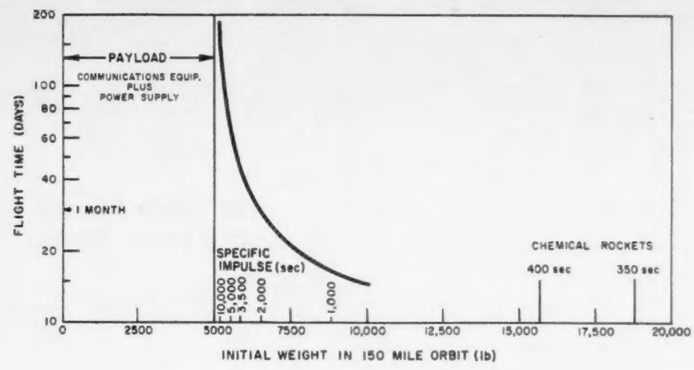
MAGNETOHYDRODYNAMICS, or magnetofluidmechanics, as I prefer to call this most modern branch of aerodynamics, has a great attraction for aerodynamicists, mainly because of some beautiful analogies to conventional fluid mechanics, which exist in the case of a conducting fluid as a result of the combination of a flow field and an electromagnetic field. The analogies which are most evident are the following:

1. The case of an ideal, i.e., nonviscous fluid, corresponds to the case of a fluid with infinite conductivity, i.e., a medium without diffusivity of electric phenomena. Therefore, two groups of beautiful examples can be investigated and compared immediately with conventional gas dynamics problems. First, there is the theory of objects placed in the combined flow and magnetic fields, i.e., a theory analogous to the ordinary theory of lift and drag of moving objects. The analogy to boundary layer phenomena is of great beauty and interest. For the case of finite but large conductivity, one finds that the effect of walls—for example, walls of insulators, at which the magnetic field strength vanishes—is restricted to a domain in the immediate neighborhood of the walls. We remember that this is the main feature of the boundary layer theory in conventional fluid mechanics. Outside this domain, the flow can be approximated by the flow in a nonviscous fluid. Conditions are analogous in the case of a magnetic field imposed on a fluid with large conductivity. And, as in the case of conventional fluid mechanics, a slip at the wall would cause infinite shear stresses. In the magnetofluidmechanical case, a jump in the value of magnetic field strength would cause electric currents of infinite intensity—for example, a current sheet of infinite current density perpendicular to the plane of the flow and the magnetic field.

Acceleration of a plasma jet, like this one generated by an Avco multiple arc, represents one promising application of magnetofluiddynamics to propulsion.

Extension to Hydromagnetics

2. The second group of analogous problems deals with the extension of the supersonic phenomena to the hydromagnetic case. The fact that there are two fundamental velocities of propagation of a perturbation, the sound velocity and the so-called Alfven velocity (i.e., the velocity of propagation of perturbations in the magnetic field strength and certain velocity components along the magnetic field lines) furnishes a rich variety of possible elliptic and hyperbolic flow domains. The simple case of stationary wave- (CONTINUED ON PAGE 86)



Flight to a 24-Hr "Stationary" Orbit

Plasma propulsion of spacecraft

Near-earth missions, such as placing a stationary satellite in orbit, call for specific-impulse ranges natural to plasmajet systems

By Morton Camac

AVCO-EVERETT RESEARCH LABORATORY, EVERETT, MASS.

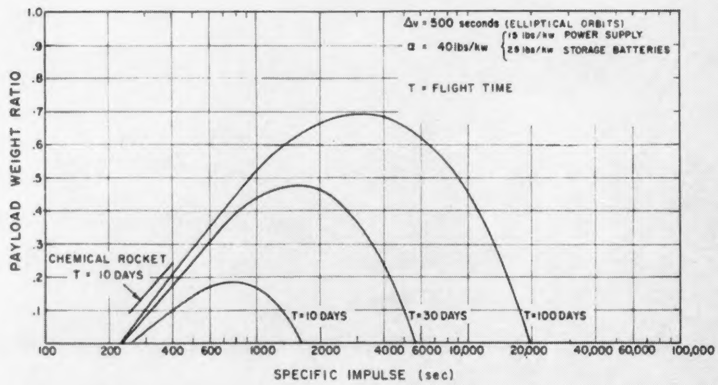
IT WAS first suggested many years ago that spaceflight beyond a low satellite orbit could be accomplished more readily with electrical than with chemical propulsion. The inherent advantage of an electrical propulsion system is that it can expel matter at velocities much higher than those obtainable with the best chemical propellants. Recently, this possibility has received a great deal of discussion and has been the spur for a considerable amount of research and invention.

Any discussion of electrical or any other space propulsion system must include some consideration of the mission. For a great variety of missions, the propulsion of vehicles only beyond a low-altitude satellite orbit need be considered. Among these, in order of increasing propulsion requirements, are rendezvous maneuvers and other orbit corrections, flight to the 24-hr "stationary" orbit (22,500 mi altitude), lunar flights, and interplanetary flights. Obviously, the missions in the gravitational field of the earth and to the moon have immediate practical interest.

We will now show that for these near-earth missions electrical propulsion systems have optimum operation when the specific impulse is in the range of 1500 to 5000 sec (corresponding to exhaust velocities of 48,000 to 160,000 fps). Even though higher specific impulses —in excess of 100,000 sec—are feasible with electrical propulsion, operation at the lower exhaust velocities gives the best performance. This is contrary to the situation with chemical rockets, where the highest obtainable specific impulse is best. This difference arises because the working fluid and source of energy are separate items in electrical propulsion.

Morton Camac is a principal research scientist with Avco-Everett Research Lab, doing research on the chemistry of high-temperature air and magnetohydrodynamics. He received B.S. (1943) and Ph.D. (1951) degrees in physics from the Univ. of Chicago and Cornell Univ., respectively, and in the interim worked on the Manhattan Project, where he investigated and identified several radioactive isotopes, and at Los Alamos Scientific Laboratory, where he constructed fast reactors and made measurements on neutron flux. As a professor of physics at the Univ. of Rochester from 1951 to 1956, when he joined Avco, Dr. Camac investigated pi mesonic atoms and pi meson scattering from hydrogen.

Dr. Camac notes that his discussion of magnetohydrodynamic propulsion represents an abstract of the work of many people, and in particular H. Petschek and G. S. Janes, at Avco-Everett under the direction of Arthur Kantrowitz.

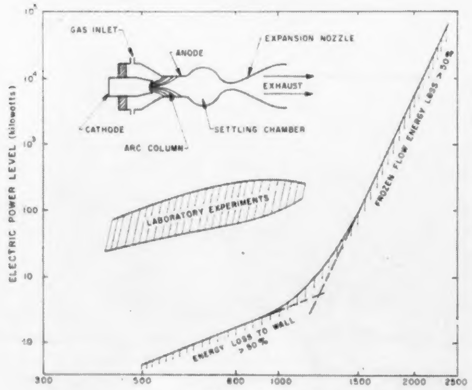


Round-Trip Mission to a Lunar Orbit

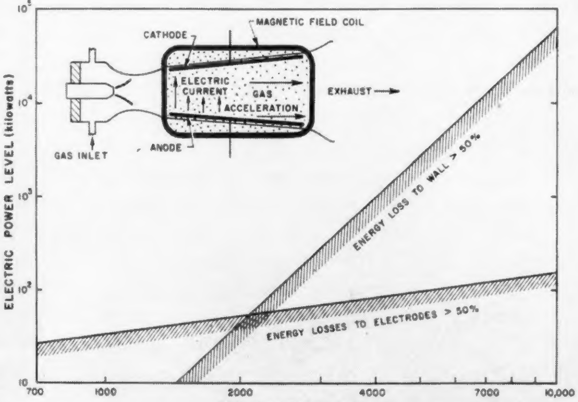
The significant weights of the electrical propulsion system will be in the power supply and the propellant. The distribution of the total weight between these two major parts is determined by the magnitude of the exhaust velocity. For a given mission, the propellant required is approximately inversely proportional to the exhaust velocity, while the power requirement (or the powerplant weight) is approximately proportional to the exhaust velocity. A minimum total system weight is obtained when the powerplant, including propulsion unit, and propellant weights are equal. Thus, for a given powerplant weight per kilowatt, specifying the mission determines the specific impulse for optimum performance.

The communications satellite is a favorable example of the possible early use of electrical propulsion, because the same electric power supply used for propulsion can also be used to power the communication system. The figure on the preceding page shows the advantage of electrical propulsion for placing a communication satellite in a 24-hr orbit (22,500 mi) starting from a low-altitude orbit. The flight-time in days is plotted as a function of the initial weight that must be lifted into the 150-mi orbit in order to transfer a 5000-lb payload to a 24-hr "stationary" orbit. The electric power supply is part of the payload, since it is used both for maneuvering the satellite in orbit and for powering the communication electronics. A 50-lb/kw specific weight was assumed for the electric power supply. The lines shown for chemical rockets give the initial weight requirement for specific impulses of 350 and 400 sec.

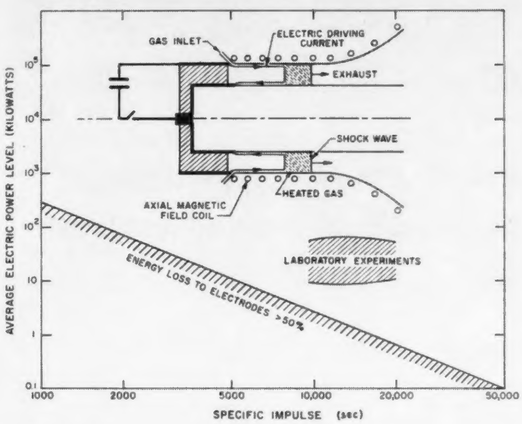
Arc Jet and Its Efficient Operating Range



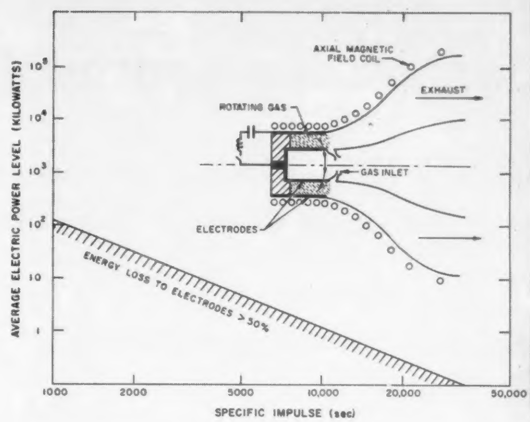
Low-Temperature MHD Accelerator and Performance



MHD Shock Tube and Performance



MHD Rotor Accelerator and Performance



If chemical rockets are used to make the transfer, then the weight that must be boosted into the 150-mi orbit will be of the order of 20,000 lb. On the other hand, assuming two months is a reasonable time for putting the satellite in orbit, only 6000 lb are required at the 150-mi orbit if the transfer is made with electrical propulsion—a reduction by a factor of 3 in the weight that must be lifted into orbit. This weight saving indicates that electrical propulsion should substantially reduce the cost of placing a communication satellite in a "stationary" orbit. Note that operation above a specific impulse of 5000 sec is not practical, since flight-time increases rapidly but the weight requirement does not decrease appreciably.

The figure at top of page 32 shows payloads for a round trip from low-altitude orbit to lunar orbit and return. The payload weight ratio is plotted as a function of the specific impulse, with the flight-time in days as a parameter. The payload weight ratio is defined as the useful payload, excluding the electric power supply, divided by the weight which must be placed initially in a 150-mi circular orbit. Note that there is a maximum value to the payload which is a function of the total flight-time. These maxima occur for operation in the specific-impulse range beween 1500 and 5000 sec. Operation above 5000 sec would require much longer flight-times with only a small gain in the payload weight ratio.

For round trip to a lunar orbit, the thrust device must produce a velocity increment (Δv) of 16,000 fps. It can be shown that elliptical-orbit flight, in which thrust is applied along a portion of the orbit, has a better performance (CONTINUED ON PAGE 113)

Flight Parameters for Round Trip to a Lunar Orbit

Propulsion system	Specific impulse (sec)	Payload weight ratio	Flight-time for propulsion system, specific weight (α) in lb/kw: $\alpha = 10$	$\alpha = 40$	$\alpha = 100$
Chemical rocket	350	0.20			
	400	0.24			
Electrical-propulsion arc heater	1100	0.37	10 days	20 days	45 days
	1500	0.50	12	35	76
Magnetohydrodynamic (MHD) devices	2000	0.60	15	50	126
	5000	0.81	69	275	690
	15,000	0.94	580	2300	5800
Ion rocket	10,000	0.90	260	1050	2600
	15,000	0.94	580	2300	5800

Cesium-ion propulsion

Ion motors for spacecraft appear within the reach of present-day technology, but geometrical design and development tests pose difficult technical problems

By A. T. Forrester and R. C. Speiser

ROCKETDYNE, DIV. OF NORTH AMERICAN AVIATION, INC., CANOGA PARK, CALIF.

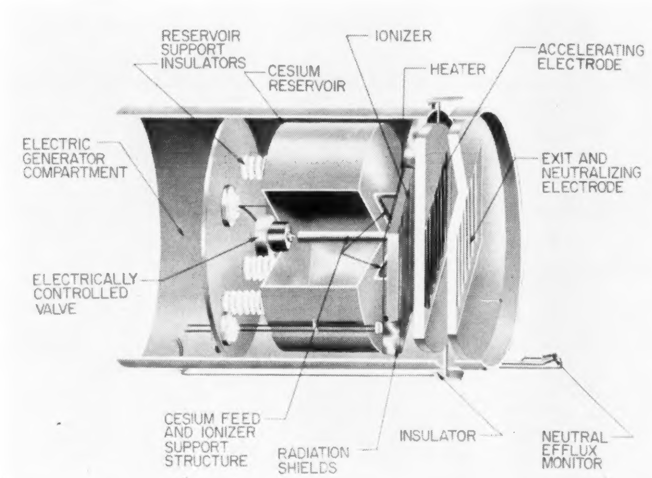
Forrester Speiser

At the time this article was prepared, A. T. Forrester directed propulsion research and experimentation in Rocketdyne's Electric Propulsion Unit. He is now a senior member of the technical staff, and head of the Ion Motor Lab of Electro-Optical Systems, Inc. After receiving a Ph.D. in physics from Cornell Univ. in 1942, in high-intensity ion sources and electromagnetic methods of separating isotopes, Dr. Forrester worked at Berkeley and Oak Ridge on the electromagnetic separation of uranium isotopes, and then with the Univ. of Southern California and Westinghouse Research Laboratories. He has published papers on ion sources, isotope separation, mass spectroscopy, electrical fluctuation phenomena, coherence properties of radiation, the photoelectric effect, optics, superconductivity, and related subjects.

R. C. Speiser is a senior research engineer in Rocketdyne's electrical-propulsion group. After receiving a B.S. in physics from CIT in 1954 and an M.S. in physics from Columbia Univ., he joined Rocketdyne in 1957. He has worked on problems associated with the physics of chemical rocket exhaust, low energy nuclear physics, inertial guidance, and experiments in ion propulsion.

FOR a rocket in which the exhaust is produced by accelerating charged particles with electrical power generated on the vehicle, there is an optimum exhaust velocity determined by a compromise between requirements of the motor for power and expellant. The optimum covers a range from 10^6 to 2×10^7 cm/sec, depending on the mission, the weight of generating equipment, and the focus for optimization—trip time, payload, or other parameter.

One of the many ways of producing such velocities is through the electrostatic acceleration of charged particles, and the first important consideration for this scheme is the ion generation itself. A technique for generating ions, which is outstanding for its simplicity, is surface ionization. In this process, atoms of some elements evaporating from an appropriate surface come off as ions. Ions of all of the alkali metals can be formed in this way; and in the case of cesium, the heaviest of the stable alkalis, this ionization is extremely efficient. It can be demonstrated that for the ion motor there is an advantage in using ions as



Isometric representation of a 0.4-lb, 6-month's duration ion motor based on data of column C in the table on page 35. Slit sizes and interelectrode spacings are shown disproportionately large.

heavy as possible and that cesium becomes the obvious material to use with the surface-ionization process.

The sources of ions most commonly used in laboratory experiments are arc sources; but the combined requirements of obtaining a very high percentage of ionization, low-power losses, a single ionic species, and a well-defined beam in a device with an extraordinarily long lifetime are difficult to meet with arc sources. Accordingly, our attention will be given to the cesium surface-ionization source.

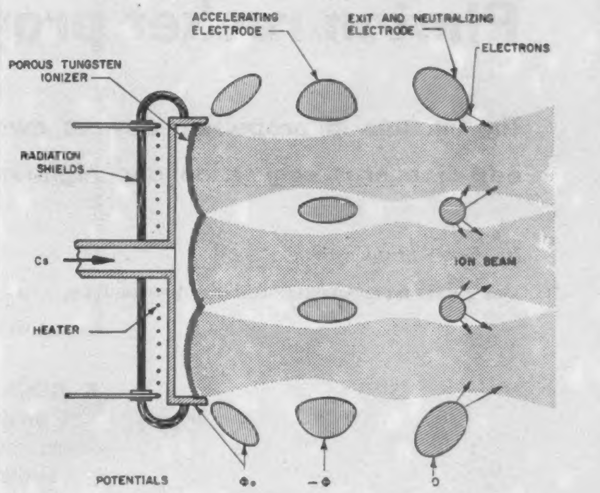
Advantage of Heavy Ions

It was mentioned that there is an advantage in the use of heavy ions. This advantage lies in the fact that heavier ions permit a smaller, lighter source-electrode system. This advantage ceases to be important once the motor becomes a very small fraction of the total ship weight, a situation which is achieved for cesium ions in the exhaust velocity range $4 \times 10^6 < v < 2 \times 10^7$ cm/sec. It will be seen that power efficiency considerations also limit the cesium-ion motor to this domain.

In the useful domain $10^6 < v < 4 \times 10^6$ cm/sec, heavier ions would be desirable, and charged colloidal particles offer some hope for this region. The use of such particles requires a completely different set of considerations, and for purposes of this discussion the region of exhaust velocities less than 4×10^6 cm/sec is excluded.

It should be realized that the exhaust velocity optimization is not critical, and that factors such as efficiency and reliability may dictate the use of motors for which exhaust velocities are different than those suggested by a simple mission analysis. Accordingly, the ion motor may not arbitrarily be rejected for application to relatively short-range space missions, e.g., changes in satellite orbits.

Schematic of a Cesium-Ion Motor



With a surface-ionization source of ions, an ion motor may be approximately as illustrated in the schematic above. Cesium is delivered to a box made of molybdenum, or (CONTINUED ON PAGE 92)

Characteristics of Several Ion Motors

A	B	C	D	E	F	G
v(cm/sec)	2×10^7	2×10^7	10^7	4×10^6	4×10^6	4×10^6
Φ_0(kv)	27.5	27.5	6.9	1.1	1.1	1.1
a/g*	10^{-4}	10^{-4}	2×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
j(ma/cm²)	6.9	1.9	3.6	7.0	7.0	15
T(°K)	1400	1310	1360	1410	1410	1470
s(cm)	1.3	2.2	1.0	0.16	0.33	0.32
Φ_1(kv)	25	17	18	2.1	7.1	11.7
$\Phi a/s$(kv/cm)	40	20	25	20	25	40
$R_A\left(\frac{\text{neutrals}}{\text{ions}}\right)$	0.017	0.009	0.014	0.019	0.019	0.027
$R_B\left(\frac{\text{radiation}}{\text{beam power}}\right)$	0.02	0.05	0.12	0.5	0.5	0.3
$R_C\left(\frac{\text{motor weight **}}{\text{total weight}}\right)$	0.0075	0.027	0.057	0.18	0.18	0.086

* Based on a total ship weight of 22.5 lb/kw.
** Based on a total ship weight of 22.5 lb/kw and an ion-motor weight of 0.032 lb/cm².

Photon rocket propulsion

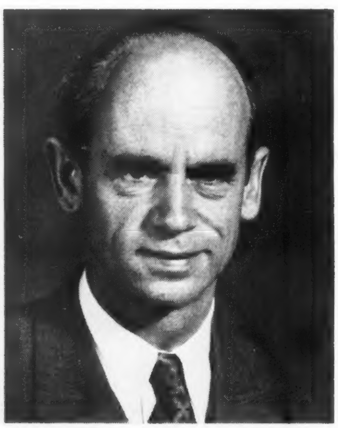
The ultimate in propulsion devices awaits entirely new methods of energy conversion and high-temperature technologies

By Ernst Stuhlinger

ARMY BALLISTIC MISSILE AGENCY, HUNTSVILLE, ALA.

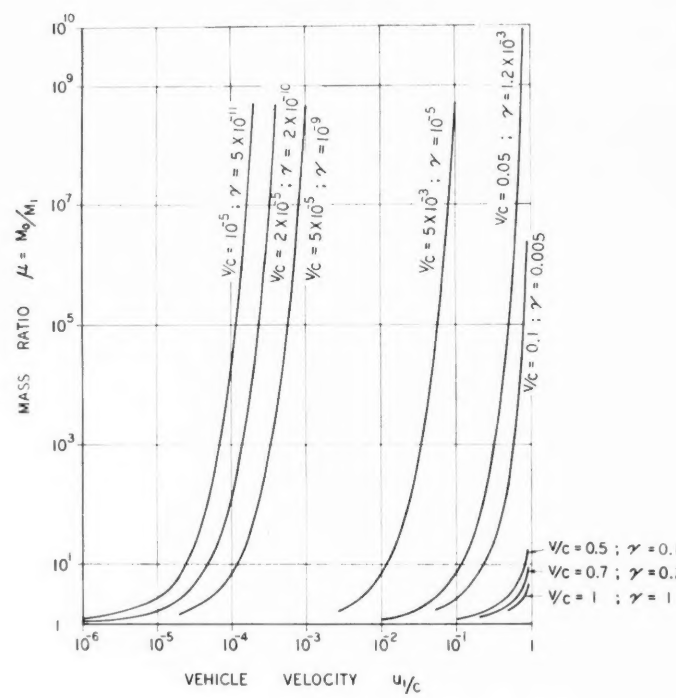
A ROCKET motor is usually characterized by its exhaust velocity. Conventional motors have exhaust velocities of the order of 2500 m/sec; advanced designs may go as high as 5000 or 10,000 m/sec. A considerable effort is continuously underway by engineers and scientists to push exhaust velocity as high as possible. The ultimate velocity is, of course, that of electromagnetic radiation, or "photons," commonly known as light velocity (c).

Photons exert a reactive force upon the source from which they are emitted. Each photon carries a well-defined momentum $p = h\nu/c$, where p = momentum, h = Planck's constant, ν = frequency of radiation, and c = light velocity. Momentum may be written in the alternate forms, $p = E/c = mc$, where E = energy, and m = "mass" of photon. If a source emits (CONTINUED ON PAGE 69)



Ernst Stuhlinger, director of the Research Projects Laboratory of ABMA's Development Operations Div., received his doctorate in physics at the Univ. of Tuebingen, Germany, in 1936, and was assistant professor of physics at the Berlin Institute of Technology doing research work in nuclear physics from 1936 to 1941. He joined the Peenemuende Rocket Development Center in 1943 and was active in the development of V-2 guidance and control systems. Coming to the U.S. under Army Ordnance Corps auspices in 1946, Dr. Stuhlinger did R&D work on missiles at Ft. Bliss and assisted in the V-2 firings at White Sands before joining ABMA in 1950. An ARS Fellow, Dr. Stuhlinger has in recent years gained recognition for his feasibility and design studies of spaceship electrical propulsion systems.

Rocket Potential



NOTS—Navy Rocket Center

Because the work of the U.S. Naval Ordnance Test Station is relatively unknown even in rocket circles, this issue of ASTRONAUTICS presents three articles on recent NOTS developments in advanced propulsion systems for missiles and spacecraft. These developments represent a new level in the state of the art of liquid-propellant rockets.

Situated some 60 mi north of Edwards AFB, in California's Mojave desert, NOTS is the Navy's largest shore station (larger than the state of Rhode Island) and the home of one of the world's great integrated rocket development centers, with headquarters in Michelson Laboratory. Its contributions to the U.S. Arsenal have been many and important—the 2.75-in. FFAR, Weapon A, Sidewinder, Gimlet, Zuni, Rat, AsRoc, and successors. Its research has often led the field in solid- and liquid-propellant technology, ballistics, tracking and range operation, optical and timing systems, telemetry, operations analysis, and other studies.

Canned liquid-rocket engines

On tap for the next generation of missiles and spaceships are off-the-shelf motors with integral propellant tanks and variable thrust which rival the best cryogenic and solid engines

By F. M. Fulton

U.S. NAVAL ORDNANCE TEST STATION (NOTS), CHINA LAKE, CALIF.

CANNED liquid propellants, stored on the shelf until the instant they are needed, will provide the energy for the next generation of military and space vehicles. The "can," or tank, of propellant will be an integral part of the motor, ready to open into the engine simply by releasing a burst diaphragm.

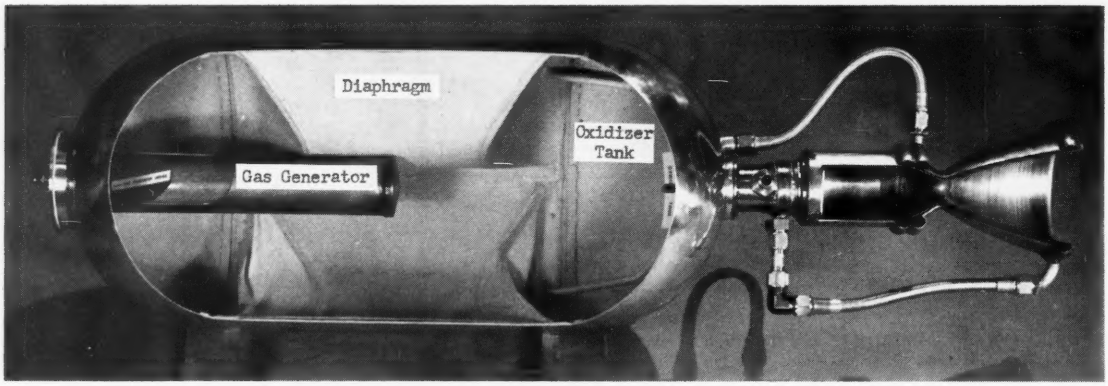
Propellants which can be hermetically sealed into propellant tanks, and which are sufficiently stable chemically to sit on the shelf for as long as five years, have already been developed and tested. These propellants already provide performance as high as, or higher than, operational cryogenic or solid systems.

A brief look at liquid and solid rocket development work in this country over the past two decades will help to point up the importance of this advance in propulsion technology.

In the main, U.S. work during this period has centered on the development of motors using either cryogenic (cold, liquefied gas) or solid propellants. The cryogenic liquids were the first to be recognized as having high potential in rocket engines for use in space vehicles. Their development was pushed by the major publicity attendant upon the initial success of the German V-2 program during WW II. As a result, German developments were incorporated into American programs at the end of the war.

Rockets using cryogenic liquids are characterized by high performance, straightforward techniques of thrust-vector control, and high-temperature combustion localized in a small combustion chamber, where it can be handled effectively by regenerative cooling. The use of liquids is attractive because the primary develop-

F. M. Fulton, a Navy veteran with a B.S. in mechanical engineering from the Univ. of New Mexico, joined NOTS in 1948 and has since risen to his present position as Head, Propulsion Development Dept. He has been a member of the Board of U.S. Civil Service Examiners for Scientists and Engineers as well as chairman of the NOTS professional recruiting panel and junior professional training program. Included in his experience is analysis, design, and development direction of complete weapon systems—both guided and unguided—for air-to-air warfare, and direction of propulsion programs for many military applications, ranging from the 2.75-in. rocket to ballistic missiles.



Cutaway of an experimental 1250-lb-thrust NOTS motor with integral tanks for high-performance propellants.

ment problems of the system can then be concentrated in the rocket-motor chamber. The motor can be static-tested repeatedly by refilling the fixed tanks with fuel and oxidizer. The use of liquid propellants also allows on-off operation of the motor.

A major drawback to the use of cryogenic liquids is the need for venting the tanks to permit the propellants to boil off until the instant of firing. Because of this, the motors cannot be stored in the loaded condition, and substantial preparation time is required to load the tanks and to top them off before rocket launching. The low density of cryogenic propellants is another drawback. Moreover, substantial difficulties have been encountered from the standpoint of ignition and combustion stability.

The end product of the cryogenic system, after 15 yr of development, is a system requiring long preparation time, very extensive ground-support equipment, and a motor that is a plumber's nightmare because of the number of valves, orifices, pumps, etc., designed into the system.

Development of solid-propellant motors started with simple, rather small ordnance units in WW II. Initially, because of their great success in small weapons, solid-propellant motors were thought to be confined to this application. But in recent years, the size and thrust levels of the solid propellants have increased greatly, so that now they compete for use in ballistic missiles. Solid-propellant rockets are noted for reliability, mechanical simplicity, instant readiness, and lack of need for extensive ground-support equipment.

The chief difficulty inherent in solid-propellant rocket motors is the necessity for solving the main problems of the rocket operation in the chemistry of the solid propellant itself. Also, the entire solid-propellant motor is exposed to the high temperatures and pressures of the rocket operation. Consequently, structural design for high mass ratio (a large amount of propellant in a small amount of structure) has been difficult to achieve. A continuing drawback of the solid rocket is the relatively poor physical properties of the propellant, which must contain a large amount of oxidizer. Finally, the one-shot operation of the solid-propellant motor necessitates the firing of a large number of full-sized motors during a development program—a costly procedure.

Fortunately, solid propellants are inherently high in density, and thus are particularly suitable for volume-limited applications. However, as the energy level of the propellants has become greater, the rocket system has become less safe. Because the oxidizer in the solid propellant must be in intimate

Established Storable Hypergolic Liquid-Propellant Systems

(Combustion-chamber pressure of 300 psi)

System	Isp, sec 1 atm	Isp, sec vacuum	σ avg (gm/cc)	Temp range (F)
IRFNA-UDMH	232	300	1.24	−65 to 165
IRFNA-Hydrazine	242	315	1.25	34 to 165
N_2O_4-JP4	230	295	1.19	20 to 250
N_2O_4-UDMH	240	320	1.10	20 to 300
$C1F_3$-Hydrazine	247	330	1.41	34 to 165

Typical High-Performance Propellant Systems Under Investigation

(Combustion-chamber pressure of 300 psi)

System	Isp, sec 1 atm	Isp, sec vacuum*
IRFNA-Li	298	400
IRFNA-$LiBH_4$	286	380
N_2O_4-$LiBH_4$	292	390
$C1F_3$–$A1(BH_4)_3$	266	355
N_xF_x–$A1H_3$	—	420

*Estimated.

contact with the fuel, safety in manufacturing and handling is jeopardized by their potential reaction, which can amount to an explosion under these conditions.

There are several alternatives to the rocket engine using cryogenic or solid propellants. One of the most attractive is a rocket engine using canned, storable liquid propellants. This engine uses fuels and oxidizers that are liquids with low vapor pressure at temperatures at which the motor is to be stored and fired.

Early interest in storable-liquid systems was dampened by the low energy levels available compared with the cryogenic systems. As a result, only relatively small programs of applied research in storable-liquid systems have been carried out in this country.

Because of this work, however, motors using canned liquids *have* been developed. These new motors are mechanically much simpler than the cryogenic motor, yet also have the advantages of regenerative cooling—concentrating the high-temperature reaction into a relatively small combustion chamber—and thrust-vector control.

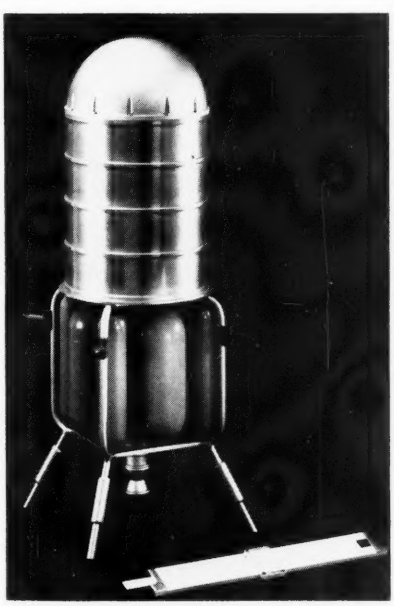
Propellant systems have been developed that can be stored for several years over wide ranges of temperature and yet be ready to fire at any time. The propellants can be loaded into the motor at the factory, thus making ground-support requirements no greater than for solid-propellant motors. Furthermore, because the propellants are liquids, the motors are free from the gross handling problems of solid rockets.

The design concept for storable-liquid systems at the U.S. Naval Ordnance Test Station (NOTS) has been based on the use of propellants that can be stored and handled safely over a minimum temperature range of —65 to 165 F. The tanks are hermetically sealed to permit loaded shipment and safe handling and storage by the user. Simple all-welded construction makes possible lightweight and durable tanks.

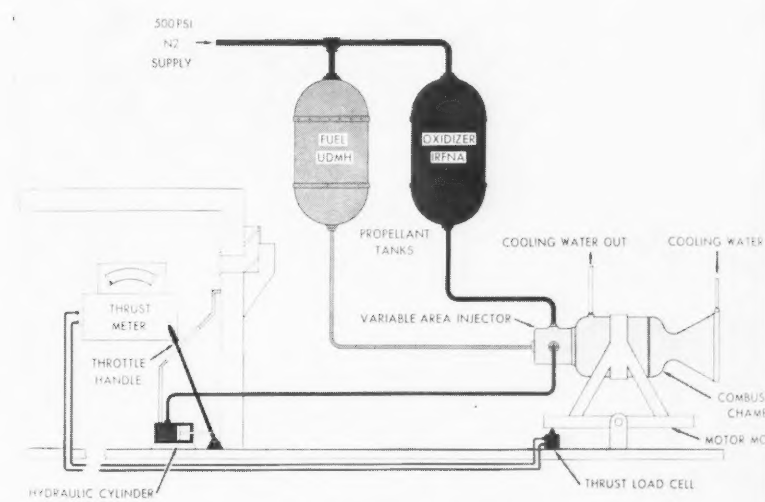
Achieving Maximum Simplicity

To achieve maximum simplicity in storable-liquid systems, they are based primarily on the use of pressure pumping, which eliminates moving parts, numerous valves, and powered pumps; and, to achieve positive displacement and to avoid pumping vapor instead of fluid, collapsible tanks, or membranes, are used to expel the liquids. The use of membranes also reduces problems of handling ullage.

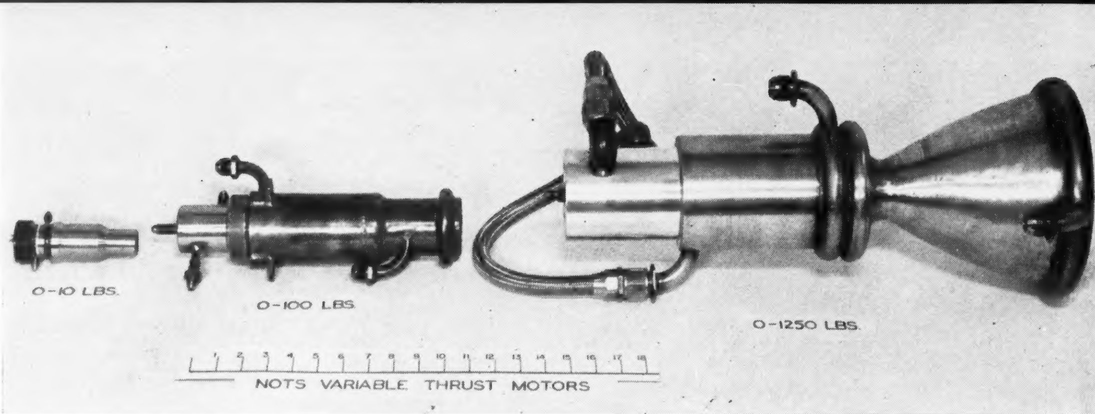
Only hypergolic propellants have been used so far. Their use eliminates ignition and combustion-stability problems. Tanks are pressurized by means of small, simple solid-propellant gas generators. The photo on page 38 shows a cutaway of an experimental 1250-lb-thrust canned-propellant motor with the features just described. (CONTINUED ON PAGE 105)



NOTS study model of lunar landing vehicle embodying canned propellant system and variable-thrust motor.



DEMAND THRUST MOTOR
RESEARCH INSTALLATION



Three sizes of NOTS variable-thrust liquid-rocket engines that deliver thrust anywhere in the design range on command and instantaneously.

Variable-thrust rocket engines

Ready off the shelf, in thrust ranges spanning a few ounces to thousands of pounds, these liquid engines promise to solve many problems of missile and spaceship power and control

By Eugene V. Rutkowski

U.S. NAVAL ORDNANCE TEST STATION (NOTS), CHINA LAKE, CALIF.

Eugene V. Rutkowski joined NOTS in 1951 upon graduation from the Univ. of Minnesota with a B.S. in mechanical engineering. He is now head of the Engineering and Development Branch of the Propulsion Development Dept., responsible for the design and development of both liquid- and hybrid-propulsion systems. His experience with storable liquid propellants has been gained from working with a wide variety of rockets, from tiny 1.5-in. motors to large, multiple, variable-thrust units. He is an ARS member of long standing, having joined in 1946.

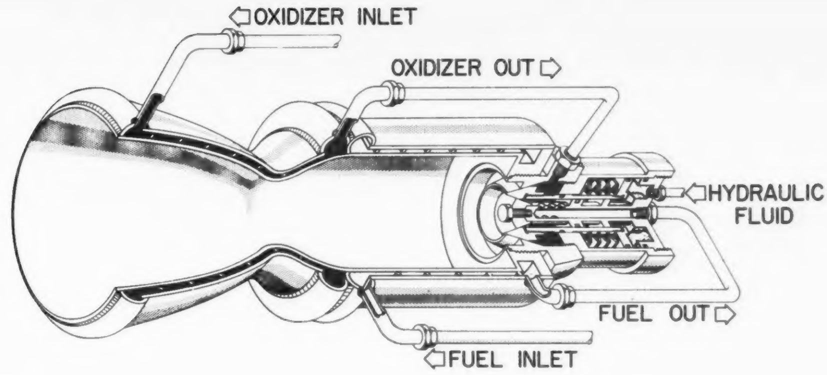
A PROGRAM of applied research in variable-thrust propulsion at the U.S. Naval Ordnance Test Station (NOTS) has resulted in the successful demonstration of complete thrust control using a basic motor design adaptable to a wide range of sizes and applications.

The photo above shows three of these variable-thrust motors, rated at 10, 100, and 1250 lb maximum thrust. The injector used in the largest motor has also been used for motors delivering up to 3500 lb thrust.

These engines respond instantaneously to commands to deliver thrusts anywhere within the entire range from zero to maximum rating. Extension of the program to include engines of both larger (0 to 15,000 lb) and smaller (0 to $^1/_{10}$ lb) thrust is underway in order to have off-the-shelf designs available for the many and varied requirements of the nation's weapon and space research programs.

Thrust control in space, where maneuvering will be required under nonaerodynamic and zero-g conditions, is one of the most important applications for these engines. Variable-thrust rockets can be used for orienting a vehicle in space or to provide acceleration or deceleration on demand. This not only makes possible vehicles of a high degree of sophistication, but can also remove a great deal of the guidance burden from the boost stages. Final corrections in the flight path of a space vehicle can thus be made after it has been launched and is in its approximate orbit.

Rocket-propelled weapons that must fly within the sensible atmosphere for any extended period of time are velocity-limited due



Design drawing of a NOTS variable-thrust engine, rated at 3500-lb maximum thrust, shows the use of both fuel and oxidizer as regenerative coolants.

to the effects of aerodynamic heating, while those flying above the effective aerodynamic sphere must maneuver by means other than aerodynamic surfaces to seek and destroy targets. In both cases, such weapon systems will require a sophisticated method of achieving thrust control.

Advancing the State of the Art

At NOTS, the applied research program in thrust-controlled rocket engines was directed toward advancing the state of the art, rather than meeting a specific propulsion requirement. The objectives were to develop smooth thrust control of a rocket engine from zero to the rated capacity of the engine, with unlimited start-and-stop capability and with engine operation for any required period.

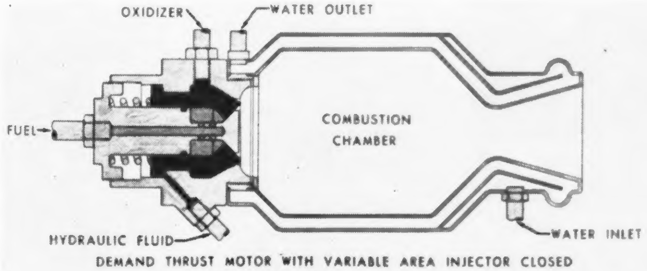
Early in this project, it became apparent that the objectives would best be met with a liquid-propellant rocket engine by control of the injection of the propellants into the combustion chamber. Some efforts were made in controlling the fluids upstream of the injector by means of valves, but it was obvious that the ultimate solution must lie in variation of injection orifice areas.

The reason for this is immediately apparent upon examination of the basic flow equation, which may be reduced to the form $\dot{w} = f\,(A\sqrt{\Delta P})$. The flow rate of the fluid ($\dot{w}$) is a linear function of the orifice area (A) and a root (fractional power) function of the pressure drop across the orifice (ΔP). To control fluid flow by controlling the pressure drop across a fixed area orifice is impractical when large variations in fluid flow are required at the maximum flow rates. The graph on page 80 illustrates the problem of fluid-flow control by injection-pressure variation compared with injection-area variation. Only injection-area variation will permit the engine designer to operate his engine at reasonable pressure levels.

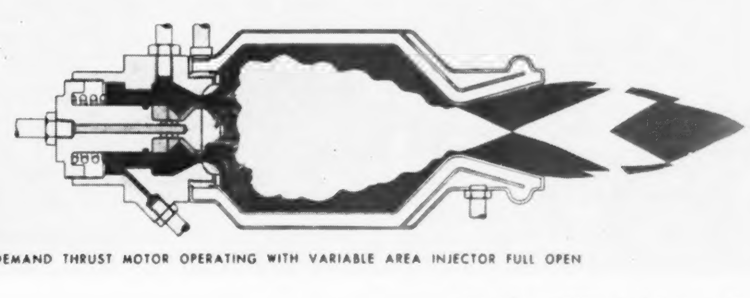
The drawings below (CONTINUED ON PAGE 80)

Demand Thrust Motor

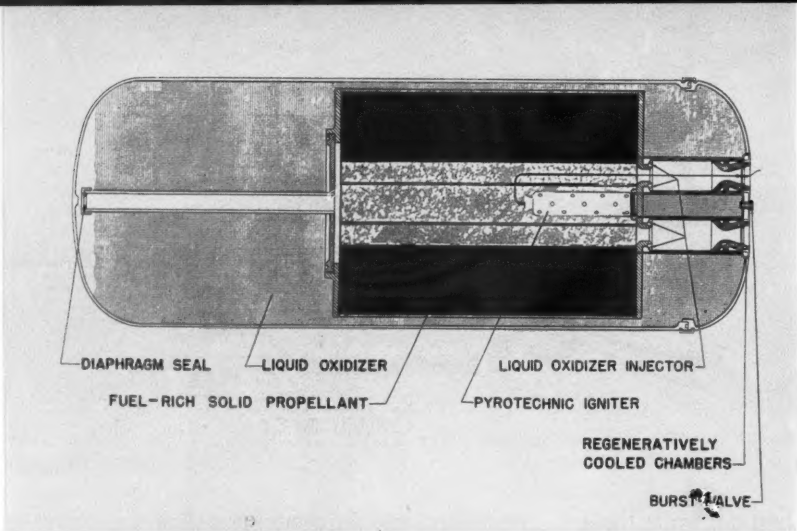
Elements of NOTS injection system for variable-thrust control. This demand-thrust system represents the successful solution of a long-standing problem in liquid-propellant rocketry.



DEMAND THRUST MOTOR WITH VARIABLE AREA INJECTOR CLOSED



DEMAND THRUST MOTOR OPERATING WITH VARIABLE AREA INJECTOR FULL OPEN



Typical NOTS hybrid (solid-liquid) rocket motor. Such motors may attain specific impulses as high as 365 sec, density specific impulses as high as 700 sec.

Hybrid propulsion systems

Solid-liquid rocket systems offer specific impulses as high as 365 sec, high-density loading, and safe handling

By Douglas D. Ordahl

U.S. NAVAL ORDNANCE TEST STATION (NOTS), CHINA LAKE, CALIF.

Douglas D. Ordahl is head of the Missile Propulsion Div. at NOTS. After receiving a B.S. in chemistry from Stanford Univ., he entered the propulsion field in 1942 at the Hercules Powder Co., Radford, Va., and then in 1945 became a research engineer at Battelle Memorial Institute, and at the same time studied for his M.S. in chemical engineering. He returned to the propellant and propulsion field in 1950 at NOTS to continue research on the physical properties of solid propellants. Since that time his work has included research, design, development, and program direction of solid-, liquid-, ramjet-, and hybrid-propulsion systems.

FACED with the ever-increasing demand for greater ranges, higher velocities, and higher altitudes to be achieved by propulsion systems of smaller size and lighter weight, the missile designer is constantly on the lookout for propellants with greater density and specific impulse. To achieve these new goals, scientists must consider many new and extreme combinations of propellant materials, including literally everything in the periodic table of the elements.

Thermodynamic calculations show that, by using radical combinations of reactants, it is possible to make great improvements—even over the most advanced propellants in use today. Progressing from theoretical calculations to a consideration of practical development of propulsion systems using the high-energy propellants immediately uncovers several significant problems. Among the most troublesome of these are the following:

1. High-energy reactions produce flame temperatures well above the range that can be handled without efficient insulation or cooling of available construction materials.
2. Many of the interesting combinations are vigorously reactive and must be positively separated for reasonable safety in storage and handling.
3. Many of the combinations offering highest performance require reactions between solids and liquids, rather than between all-solids or all-liquids, as employed in the more familiar propulsion techniques in general use.

Scattered through the classified literature on rocket propellants are accounts of attempts to use the solid-liquid, or *hybrid*, approach

as early as 1933. Among the more active investigators in this field have been Rocketdyne and Experiment Inc. Because of the great potential of hybrids for missiles, the U.S. Naval Ordnance Test Station has also investigated hybrid systems and has undertaken development of hybrid propulsion units.

The general principles underlying a new method for using hybrid propellants under development by NOTS can be seen in the design drawing on the opposite page. This schematic shows a typical motor using a fuel-rich solid propellant and a storable liquid oxidizer, such as nitric acid. The solid propellant is ignited in the usual manner to produce fuel-rich gases that flow into the combustion chamber. When it ignites, the solid-propellant motor also pressurizes the head-end space in the rocket, rupturing low-pressure diaphragm seals and in turn pressurizing the surrounding tank of liquid oxidizer. The oxidizer then flows through an injector and mixes with the fuel-rich product from the primary reaction. The secondary reaction oxidizes the fuel to the stoichiometric point or beyond, producing high-energy combustion at very high temperatures. In this manner, a high-performance propulsive force is generated that is proportional to the flow rate of the oxidizer.

By using relatively fuel-rich solid propellants, of the type commonly employed for gas generators, and red fuming nitric acid, it has been demonstrated that valving the oxidizer allows control of the total thrust over a ratio of approximately 3:1. Specific impulses of the first systems tested varied from approximately 180 to 245 sec as the total flow rate was controlled over a range from about 3:1.

The first exploratory experiments to evaluate this hybrid method achieved the theoretically predicted results within ordinary limits of experimental error. Over 300 subsequent experiments have proved the practicality of the approach and indicated outstanding promise for both high-energy and high-density systems that can be adapted to motor designs of any foreseeable size for chemical propulsion. Excellent agreement has been demonstrated between theoretical calculations and actual measured data in motors up to 8 in. in diameter.

Performance levels achievable with materials already available actually exceed those predicted for the best available high-energy solids. As an example, a specific impulse of between 255 and 265 sec has been demonstrated for a common nonaluminized double-base solid propellant with an ordinary halogenated oxidizer.

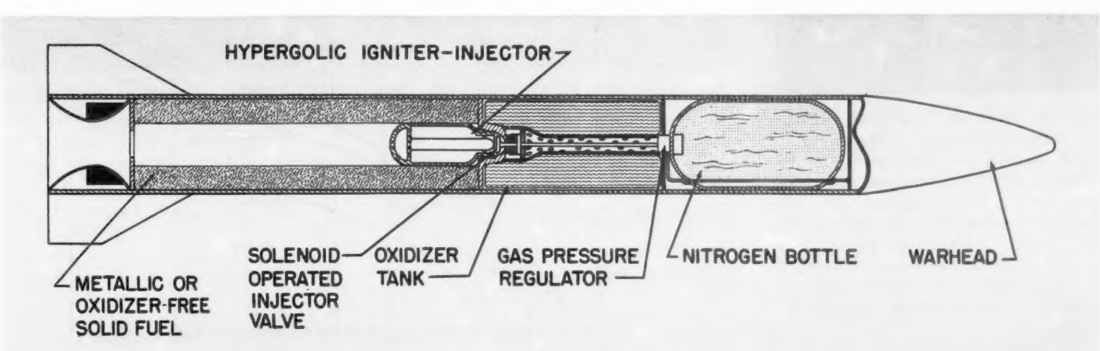
Calculations based on fuels and oxidizers designed especially for use in hybrid systems indicate specific impulses up to 365 sec. Density specific impulses (density $\times$ specific impulse) as high as 700 sec are achievable in practical systems using existing materials.

Design Studies and Tests Made

Extended design studies have been made to consider a number of possibilities for the use of hybrid propulsion systems, and flight-type test vehicles have been constructed for units up to 6.5 in. in diameter. In spite of the use of an afterburner or secondary combustion chamber, propulsion systems of the 1000-lb total-weight class have been designed that achieve mass ratios between 0.85 and 0.90.

In addition, experimental work, as well as design studies, have been carried out for systems using head-end injection in which the oxidizer is sprayed over the fuel charge. By the use of charges of pressed metal fuel with less than 10 per cent binder and sustaining oxidizer, complete on-off and modulated thrust control has been achieved by valving the flow of the oxidizer over the charge.

The only difficulty in using a hybrid system, such as that shown below, is the necessity to pressurize the oxidizer tank above the pressure of the combustion chamber. This can be (CONTINUED ON PAGE 84)



Hybrid propulsion system using head-end injection to attain complete thrust-control capability.

Free-radical fuels—A tough problem

Though no bed of roses, free-radical research has brought advances, and kept up hopes for a breakthrough in propulsion

By John M. Flournoy

AEROJET-GENERAL CORP., AZUSA, CALIF.

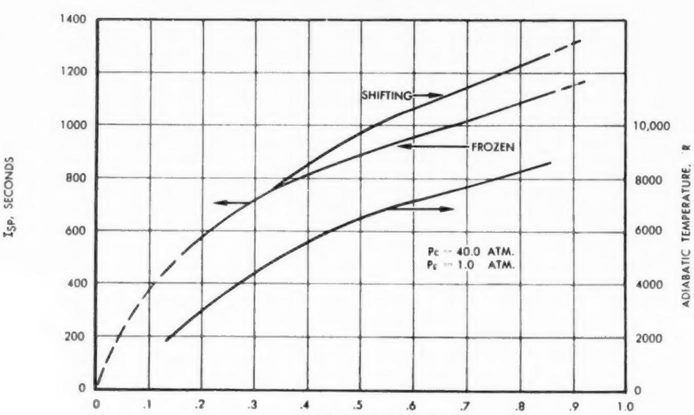
FOR THE past few years, most discussions of advanced propulsion systems have included at least some mention of the very high specific impulses theoretically attainable with stabilized free radicals. The energy of these systems is derived entirely from the heat of recombination of trapped atoms. They can, therefore, be regarded as monopropellants. It seems appropriate to review the problems involved in the utilization of these elusive chemical fragments in the light of research results during the past two or three years. Four basic problem areas can be defined, namely: (1) selection of candidate systems, (2) production techniques, (3) storage requirements, and (4) combustion properties.

Though many stabilized atom systems have been considered, one of these stands out as especially interesting–mixtures of atomic and molecular hydrogen. Impulse data for this system are summarized in the graph, which was prepared by the General Electric Co. Of the other most promising looking systems (O in O_2, N in N_2, F in F_2, and mixture of these with helium), several exhibit calculated impulse figures near 400 sec in compositions containing 50 mole per cent or more of atoms. This represents only a rather slight gain in impulse over, say, the molecular H_2-F_2 system (maximum specific impulse about 380 sec). (CONTINUED ON PAGE 106)

John M. Flournoy is project chemist for Aerojet-General's AFOSR sponsored free-radical program. He received a Ph.D. in physical chemistry from the Univ. of Southern California after graduation from Georgia Tech. Dr. Flournoy's background includes a year of study at the Univ. of Munich on a Fulbright and several year's experience in experimental reaction kinetics.

The research program on free-radical stabilization at Aerojet-General is being supported by AFOSR under Contract AF 18(603)-110.

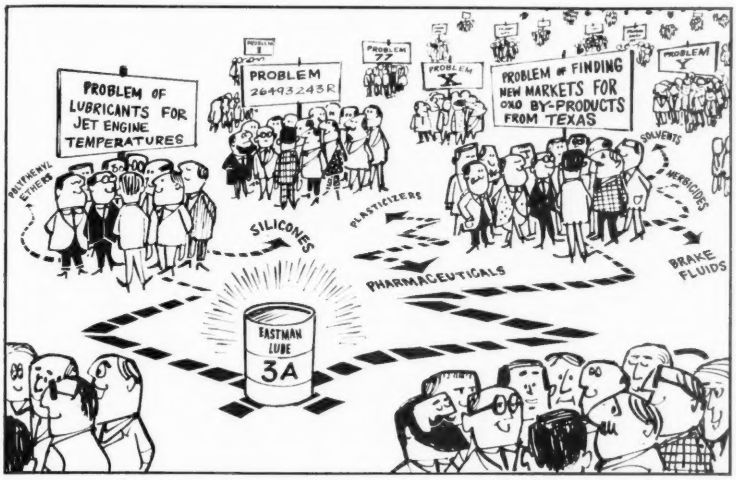
Calculated Performance of Free-Radical Hydrogen Systems



Kodak reports on:

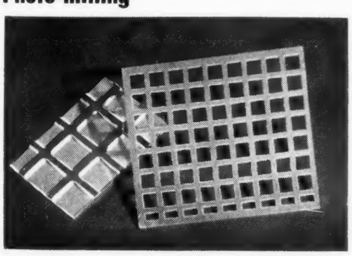
how modern scientific research is organized . . . a new method of metalworking . . . a method for forecasting titanic stress in fine detail

The hot oil project



That, roughly, is how these things develop. The principal constituents of *Eastman Lube 3A* are straight-chain fatty acid esters of trimethylpentanediol, a compound obtained by a certain setting of the valves at our "oxo process" plant in Longview, Texas. No other of the 16 currently accepted 350°F lubricants does so well in the crucial lead corrosion test as *Eastman Lube 3A*, which doesn't even require a special additive to keep it from attacking lead after six months. On the other crucial tests demanded by MIL-L-7808C, *Eastman Lube 3A* makes out OK. Those who need further facts to be impressed can write Eastman Chemical Products, Inc., Kingsport, Tenn. (subsidiary of Eastman Kodak Company), where friendships formed at a comparatively cool 350°F are expected to warm with the hot pursuit of lubricity to higher temperatures but never in themselves to prove lubricous.

Photo-milling



New methods of metalworking do not come along often enough to be ignored. Here are two examples of what we call "photo-milling." The one on the right could, of course, have been done on a punch press if die cost had been justifiable. No die was used, nor were the openings cut individually. The one on the left looks like a milling machine job, for sure. It isn't.

This sort of thing is now best done photographically with a new light-sensitive preparation called *Kodak Metal-Etch Resist*. You spray it on, or dip, and dry. Then you expose to bright light under a film on which you have photographed the pattern. After a simple development, a flush that washes away the resist where the pattern kept the light off, and a bit of baking to remove the developer solvent, the metal is ready for whatever chemical or electrolytic etching works best. The resist protects from etching action vigorous enough to remove a quarter-inch of aluminum and considerable depths of stainless steel, tool steel, magnesium, titanium, and possibly some metals we know nothing about. To get the benefit of our thinking on the subject, write Eastman Kodak Company, Graphic Reproduction Division, Rochester 4, N. Y.

Photoelasticity by the slice

Westinghouse, long known as a hotbed of photoelastic activity, has been nice enough to cast upon the waters of industrial co-prosperity a piece of technique that could help sell more *Kodak Contour Projectors*. No time must be lost in spreading the word. Too long have we touted photoelastic stress analysis with no brighter prospect of gainful return than seeing a little film put to good use in recording the pretty patterns.

Westinghouse took one of these projectors of ours, a non-photographic optical-mechanical device intended for the checking of dimensions on enlarged images of mechanical parts, and they turned it into a magnifying polariscope. This they did in the interest of reaching reasonable decisions on the mechanical design details to enable a nuclear reactor pressure vessel to withstand the titanic stresses that it must bear.

Scale models were built out of a certain transparent epoxy resin which not only exhibits the well known differential retardation between light polarized parallel and perpendicular to the stresses, but can retain the effect "frozen in" after the pressure is released and the model is literally sliced up in various planes of interest to the stress analysts. Instead of yielding average values of stress over the areas where electrical resistance strain gages happen to be bonded, this method shows how the stress pattern builds up to ominous levels at points suspected or not. The *Kodak Contour Projector* is what brings the stress analyst in close, past the gross structure of the pattern, to the all-important fine details where structural failure starts.

Don't bother Westinghouse for a description of the optical, mechanical, and electrical additions they've made to the projector. It's enough that they are publishing a full description of the analytical method (Proceedings of the Society for Experimental Stress Analysis, *17*, No. 1). *They're not interested in selling projectors. Eastman Kodak Company, Special Products Division, Rochester 4, N. Y., is.*

This is another advertisement where Eastman Kodak Company probes at random for mutual interests and occasionally a little revenue from those whose work has something to do with science

Kodak
TRADE MARK

Advanced Reactor Concepts

(CONTINUED FROM PAGE 22)

terial in the earliest papers on nuclear rockets by Tsien, Shepherd and Cleaver, and Seifert. The graphite reactor can be visualized simply as a block of graphite with a uranium compound dispersed within it. The block is pierced with passages to permit the propellant to flow through and remove the heat generated by the fissioning uranium.

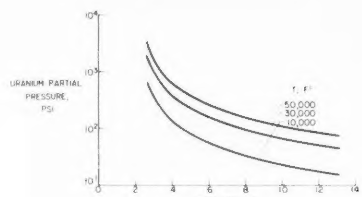
Graphite, however, is seriously limited by the chemical corrosion of hydrogen. To use graphite at its full temperature capability, hydrogen-resistant coatings on the graphite, or corrosion inhibitors mixed with the hydrogen, must be used. Coatings are a difficult problem with graphite, especially if the reactor is to be temperature cycled, since graphite has a very low expansion coefficient compared with any likely coating material. On the other hand, inhibitors added to the hydrogen will increase the average molecular weight of the working fluid and therefore reduce specific impulse.

Of the metals available for solid-fuel-element reactors, tungsten with a melting point of about 6100 F is the most refractory. Compared to graphite, the physical properties of tungsten at elevated temperatures are not very well known. Tungsten, however, is resistant to corrosion by hydrogen at all temperatures up to the melting point. It seems reasonable to expect tungsten fuel elements to operate at temperatures of about 5000 F, assuming that a uranium compound, such as uranium dioxide, can be retained in the fuel elements at this temperature. Inasmuch as tungsten is not a moderator, a separate moderating material must be incorporated into the reactor. In a sense, this provides flexibility for the designer, since a better moderator than graphite can be chosen to give a smaller, lighter reactor. On the other hand, a moderator which is not integral with the fuel element requires a cooling system, and thus complicates reactor design.

Tungsten Problems

A difficult obstacle posed by the use of natural tungsten is its high thermal neutron capture cross-section and strong capture resonances. The high cross-section requires that about 30 to 40 per cent by volume of the fuel element be a uranium-bearing compound. This leads to problems in containing such large amounts of uranium compounds in tungsten-fuel elements. Fortunately, there is an isotope (184) of tungsten which has a low capture cross-section and only one rather insignificant absorption resonance. The most abundant isotope, tungsten-184 occurs to the extent of 30.6 per cent in natural tungsten. The use of this isotope will reduce the required concentration of uranium compound to less than half, which greatly simplifies the materials problems. In addition the reactor will be much smaller than is possible with natural tungsten and will require much less uranium-235 for criticality. Also, the savings in separated uranium-235 might pay for the separation of the tungsten isotope.

Gaseous-Core Reactor Characteristics



Note: D_2O reflector 45 cm thick; uranium-235 the fissionable material; spherical geometry.

One drawing on page 21 illustrates a reactor concept (Rom and Johnson) designed to produce hydrogen at 4500 F while operating at a peak tungsten-fuel-element temperature of 5000 F. The tungsten-184 isotope is used for the fuel-element material, with moderation provided by beryllium oxide, chosen because it has the highest operating temperature of any good moderating material and is also compatible with hydrogen. If beryllium oxide is not highly stressed, it should be capable of operating at temperatures approaching 4000 F. Control is provided by ganged absorbing rods symmetrically arranged in the moderating regions of the core. The design is rather conventional in principle, in that the fuel element, control rods, and moderator arrangements are rather standard. The key problems appear to be the production of tungsten-184, the containment of a uranium compound in tungsten, and the remote and automatic control of a reactor which operates over a temperature range of −400 to 5000 F.

To obtain the ultimate performance from a solid-fuel-element nuclear-rocket reactor, ceramics such as the carbides of hafnium and tantalum should be used because they have the highest melting points—near 7000 F—of known materials. Both tantalum carbide and hafnium carbide are compatible with hydrogen up to their melting points. Tantalum has a thermal absorption cross-section about the same as natural tungsten. Consequently, fuel elements made with it would have to contain 30 to 40 per cent by volume of a uranium compound, just as a natural tungsten reactor would. Unfortunately, there is no stable isotope of tantalum with a low thermal cross-section.

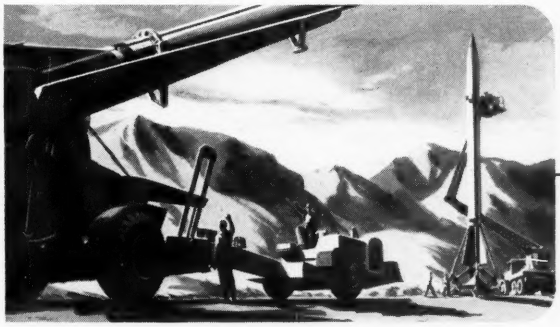
Hafnium in its natural compositions has a prohibitive thermal cross-section. But the hafnium-180 isotope, which constitutes 35.44 per cent of the natural mixture, has a thermal cross-section about two-thirds that of natural tungsten. Its use would therefore allow a reactor core smaller than a natural tungsten core, with a lower percentage of a uranium compound required in the fuel elements.

To minimize the amount of hafnium carbide or tantalum carbide in the reactor, the reactor could be constructed with successive stages of various materials which raised the hydrogen in turn to the respective limits of the materials. A drawing on page 21 illustrates a suggested reactor of this type which utilizes tungsten-184 and hafnium carbide. The hydrogen first passes through the reflector, nozzle, and other parts that require cooling. Then the flow reverses and passes through the tungsten-184 elements, which heat the hydrogen to 4500 F. The flow again reverses for a final pass through the hafnium carbide elements, where the hydrogen is heated to 6000 F. The hydrogen absorbs about one-fourth to one-third of its heat in the final pass.

Rotating Drums for Control

In this reactor, rotatable reflector drums are satisfactory for control, even though reflectors could lead to variations in radial power production in the tungsten-184 region. Nonuniformities in temperature are ironed out by mixing in the header preceding the final pass through the hafnium carbide. Nonvarying radial power distribution is important in the central region of the core, which is farthest away from the perturbing effect of the control drums.

The chief problem in the use of these carbides is probably the containing of a uranium compound in the molten state within the carbide body. The carbides will probably be capable of operating at temperatures considerably higher than 5000 F, which is the melting point of the most refractory uranium compound, uranium dioxide. Another problem is the separation of



the hafnium-180 isotope from the natural mixture. Also, determination of the nuclear characteristics of multizone reactors with widely different temperature levels existing in the reactor simultaneously, is quite formidable. Moreover, startup and shutdown of nuclear-rocket reactors employing relatively brittle materials such as the carbides, and operating at temperature levels of −400 to almost 7000 F, present challenging engineering problems.

Designing Around Ceramics

In brief, we might in summary say that ingenuity in designing around the weaknesses of ceramic materials will play an important role in the full utilization of the temperature capability of ceramic-fuel-element reactors.

The next step in achieving higher temperatures for nuclear rockets is the use of liquid-uranium compounds to heat hydrogen. Uranium carbide has a normal boiling point of about 7900 F at a pressure of 1 atm. If the hydrogen to be heated is bubbled through a porous wall or screen which contains the molten-uranium carbide, the walls can operate at a temperature below the liquid temperature.

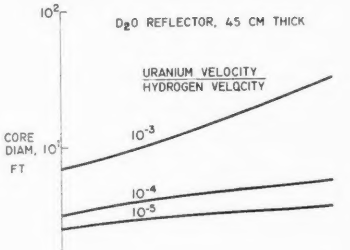
McCarthy has suggested a liquid-fuel reactor in which molten uranium is held against the porous walls of a rotating cylindrical container and the hydrogen is heated as it bubbles through the molten uranium. A drawing on page 22 illustrates a reactor concept using a rotating cylinder. The fuel is molten uranium carbide held to the cylinder walls by centrifugal force. Moderation is provided by a solid reflector material, such as beryllium. The reflector has rotating-drum-type control rods.

In this reactor, the hydrogen propellant first passes through the nozzle and then through the reflector to the gap between the rotating cylinder and the reflector. The hydrogen passes through the porous tungsten-184 walls, bubbles through the molten carbide, and finally passes out the nozzle to produce thrust. The nozzle throat is cooled by a small amount of bypass flow through a porous wall.

Aside from the problem of cooling the containing walls, the most important limitation of this reactor would be evaporation of fuel. An estimate of the vapor pressure of uranium carbide would indicate that excessive uranium carbide loss would occur at temperatures above 6500 F for an operating pressure of 1000 psia. In other words, to avoid excessive evaporation losses, the uranium carbide must operate far below the boiling point at 1000 psia. Specific impulses would at best approach about 1500 sec for the liquid reactor. Whether such a reactor should be seriously considered would depend on how practical a design can be evolved in comparison with the solid-fuel-element reactor.

Temperatures beyond the limitations imposed by the highest melting points of materials can be attained for nuclear rockets by the use of fissioning material in the gaseous state. This scheme sees the working fluid heated by direct mixing with the fissioning uranium. The working fluid might also be heated by thermal radiation from the fissioning uranium, if the working fluid has absorption bands in the energy ranges radiated. Since in these reactors the hot gas cannot be in contact with solid material, the gas must be held away from the wall by some method. It has been suggested that magnetic fields be used to suspend ionized fissionable materials. Another possibility is the use of film-cooling techniques, as suggested by Kaeppeler. The working fluid can be introduced into the reacting chamber through pores, slots, or holes to provide a cool blanket of gas over the solid walls and to remove the heat that is radiated to the walls.

Propellant Ratio Required for Gaseous-Core Reactors



Note: Ratio of hydrogen to uranium-235 flow rate is 100:1; total pressure, 1000 psia; D_2O reflector 45 cm thick.

In the gaseous-reactor concept, the fission chain reaction is maintained in a cavity reactor. Safonov and Bell have shown that critical reactors can be constructed by surrounding a gaseous mass of fissionable material with a reflector-moderator. The graph on page 46 indicates the pressure of the uranium vapor required for criticality as a function of cavity diameter and gas temperature. The calculations are based on the results of Safonov for uranium-235 gas-moderated with a D_2O reflector with a thickness of 45 cm. At a temperature of 30,000 F and a uranium pressure of 1000 psia, for example, the required reactor diameter is 3 ft.

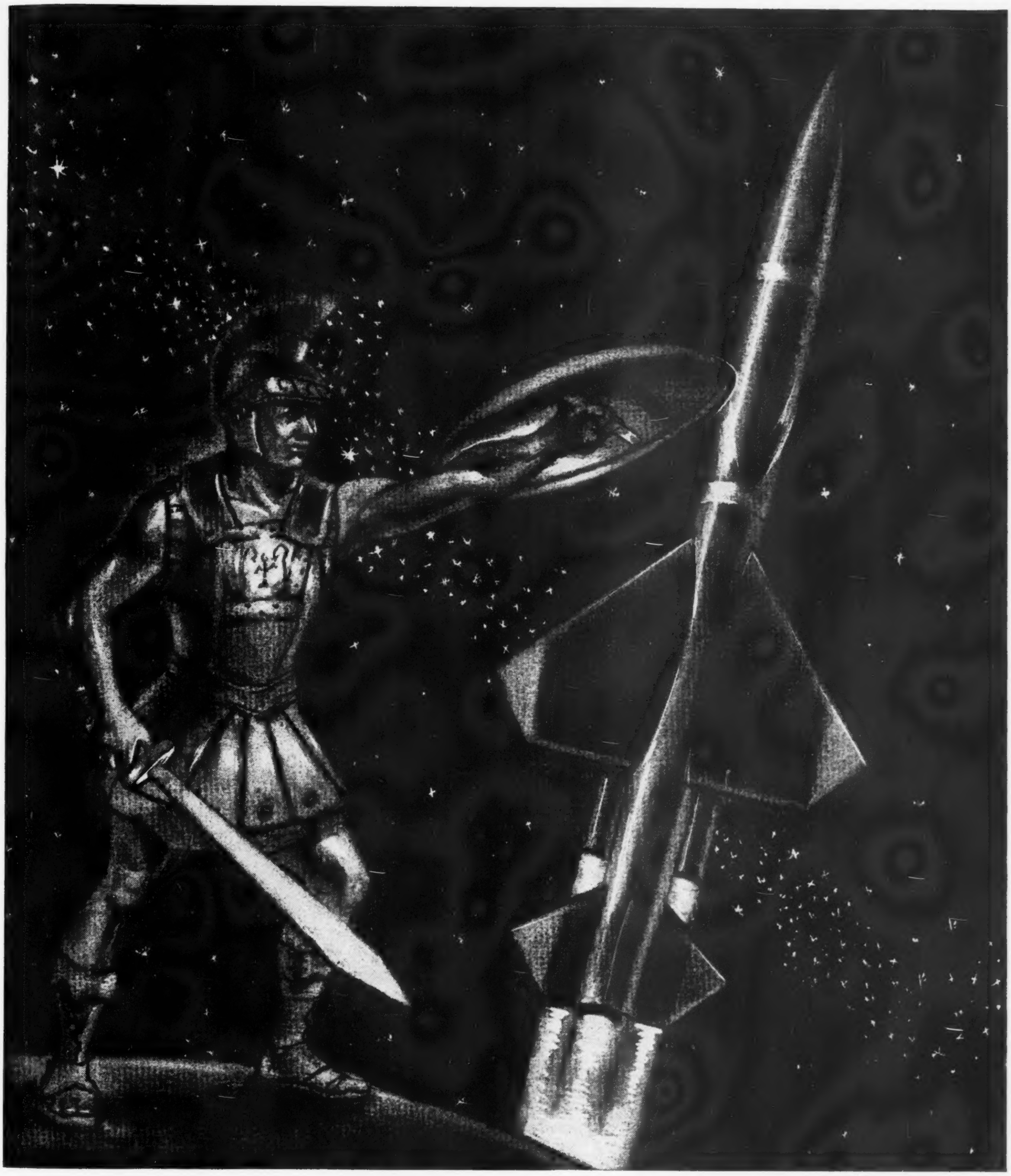
To reduce the consumption of uranium, hydrogen is used as a diluent. The hydrogen reduces the uranium partial pressure and maintains a total pressure of 1000 psia. An upper limit to a reasonable uranium consumption rate might be that the uranium consumption rate be 1 per cent of the hydrogen consumption rate. (In a rocket vehicle with a hydrogen load of 100,000 lb, 1000 lb of U-235 would be used.) The partial pressure of uranium in a mixture with this mass-flow ratio is 1/23,500 of the total pressure, if the hydrogen is assumed to be completely dissociated.

The graph at left indicates that the required reactor diameter would be enormous. To achieve a reasonable diameter value, the *uranium density must be increased without increasing its flow rate relative to the hydrogen flow rate and without increasing the over-all pressure.* This can be done if the velocity of the uranium flow is reduced relative to the hydrogen velocity in the reactor cavity. If the gases are mixed, this implies that hydrogen atoms must be diffused through the uranium atoms if the velocity difference is to be maintained.

The graph at left gives the reactor diameter required for criticality as a function of temperature for a total gas pressure of 1000 psia and for a ratio of hydrogen flow to uranium flow of 100:1. Curves are shown for several values of the ratio of uranium to hydrogen velocity, assuming that such velocity ratios can be maintained. To obtain a reactor diameter of 10 ft or less, the uranium velocity must be less than $^1/_{1000}$th of the hydrogen velocity. How can such a condition be achieved?

First of all, to overcome the diffusion forces, some external influence must produce a larger force on the uranium atoms than on the hydrogen atoms. At a temperature of 30,000 F, uranium is partially ionized, whereas hydrogen is not. This suggests the possibility of electrical or magnetic fields exerting a force only on the uranium atoms. Because of the magnitude of the diffusion forces, the magnetic or electrical fields required would be very large.

The highest magnetic fields talked about in conjunction with thermonuclear work are in the range of hundreds of kilogausses. The stronger the field



applied, the greater can be the hydrogen flow rate through the ionized uranium gas. In other words, the field strength determines the maximum permissible hydrogen flow rate. The disadvantage of using magnetic or electrical fields is that large amounts of electrical energy must be supplied. Sources of electrical energy for spaceflight are notoriously heavy and require thermal radiators to remove waste heat. A powerplant based on such a principle would suffer from the low thrust-to-weight ratios encountered with any electrical propulsion system.

Vortex Flow Field Use

Another possibility for producing larger forces on the uranium atoms than the hydrogen atoms is the use of a vortex flow field. Because the gases would travel in a circular path, centrifugal force would act on them; and, since the heavier gas atoms would have more inertia, it would take a greater force to deflect them into a path of a given radius. This action would set up a steeper radial pressure gradient in the heavy gas than in the light gas, and tend to increase the concentration of the heavy relative to the light gas outward from the center of a vortex.

A vortex can be generated in a cavity reactor by injecting the gases at high velocity through tangential nozzles located around the periphery of the cavity. The tendency to high uranium concentration toward the outside of the vortex is opposed by the net inward radial component of flow in the cavity. The balance between the radial flow effect and centrifuging action will establish a zone of high uranium concentration which is held away from the walls of the cavity. The increasing centrifugal field occurring toward the center in a vortex will prevent high cencentrations toward the center. An illustration on page 22 shows the idea of a vortex flow field reactor engine.

There are many problems to be solved before the feasibility of the gaseous vortex reactor can be determined. First of all, the ability to maintain a stable cloud in a vortex with a net radial through-flow must be established. Second, the amount of possible through-flow in such a system must be determined. There is obviously a limiting radial flow for each vortex strength beyond which the uranium cloud will be swept out. Determination of this limit will fix the thrust available from this system. Third, the cooling problems, as determined by radiation of thermal energy from the high-temperature gases to the walls of the cavity, will fix an upper temperature limit.

In addition to these problems, the cooling of the nozzle, which is heated by convection and radiation, poses a difficult problem. Most likely, a porous wall or slots which provide film cooling should be used. The reduction in temperature caused by mixing of the cooling gas with main gas flow results in the appearance of a maximum outlet gas temperature for any particular configuration. Also, the chemical compound of uranium which is injected may introduce corrosion problems. For example, it might be desirable to use a corrosive compound, such as gaseous uranium hexafluoride. Then, too, methods of injection of the uranium or uranium compound must be investigated. Still another problem arises from the coupling of hydrodynamic with nuclear effects. The reactivity of the reactor will be affected by variations within the uranium cloud. The interactions must be thoroughly investigated to see the extent to which this problem exists. The startup and control procedures may present some other difficulties.

These are some of the many problems connected with the gaseous reactor. The potential it offers makes vigorous efforts toward the solution of these problems worthwhile. The gaseous reactor, if it can be made to operate at a temperature of 50,000 F, will easily yield specific impulses as high as 3000 sec, which will make interplanetary flights with velocity increments of 30 to 50 mps as easy as placing payloads in orbit with chemical rockets.

In the limited space available, ideas such as the use of successive nuclear explosions, the use of fission fragment ejection, and many others have been neglected to permit a more detailed discussion of some of the more straightforward advanced ideas for nuclear-rocket propulsion.

More Effort Needed

More effort needs to be applied to all types of nuclear reactors for rocket propulsion. With such great gains in performance clearly possible, the nation's effort needs to be greatly expanded. In particular, research into high-temperature materials which are to contain uranium compounds needs to be emphasized. Present ideas for the containment of the high-temperature gases for gaseous-reactor concepts need to be evaluated and new ones brought into being. The ultimate capability of nuclear rockets rests with the ingenuity of the scientists and engineers of our nation, a relatively small number of which are now working on the problems to be solved.

Suggested Additional Reading

Anon, Nuclear Rockets—Beyond Tomorrow, *Nucleonics,* Vol. 16, No. 7, pp. 73–75, July 1958.

Bussard, Robert W. and Delauer, R. D., *Nuclear Rocket Propulsion,* McGraw-Hill Publ. Co., Inc., 1958.

Bussard, Robert W., *Some Boundary Conditions for the Use of Nuclear Energy in Rocket Propulsion,* ARS 13th Annual Meeting, N.Y., Nov. 1958.

Cotter, T. P., Potentialities and Problems of Nuclear-Rocket Propulsion, *Aero-Space Eng.,* Vol. 18, No. 2, pp. 50–53, Feb. 1959.

Dillaway, R. B., *Typical Propulsion Systems for Spaceflight,* Space Propulsion Session, IAS 26th Annual Meeting, N.Y., Jan. 27–30, 1958.

Grey, Jerry, *A Gaseous-Core Nuclear Rocket Utilizing Hydrodynamic Containment of Fissionable Material,* ARS Preprint 848-59, June 1959.

Grey, Jerry, Nuclear Rockets–Basic Principles, *Nucleonics,* Vol. 16, No. 7, pp. 62–65, July 1958.

Johnson, P. G. and Smith, R. L., *Round Trip Trajectories for Mars Observation,* 2nd Western Meeting AAS, Aug. 1959.

Levoy, Myron M. and Newgard, John J., Nuclear Rockets-Rocket-Reactor Design, *Nucleonics,* Vol. 16, No. 7, pp. 66–68, July 1958.

McCarthy, J., Nuclear Reactors for Rockets, *Journal of ARS,* Vol. 24, No. 1, p. 36, 1954.

Rom, F. E. and Johnson, P. G., Nuclear Rockets for Interplanetary Propulsion, *SAE Journal,* June 1959.

Safonov, G., *The Criticality and Some Potentialities of Cavity Reactors,* (Abridged), Rand Corp., RM-1835, July 17, 1955.

Sams, E. W., *Performance of Nuclear Rocket for Large-Payload, Earth-Satellite Booster,* IAS Preprint 59-94, June 1959.

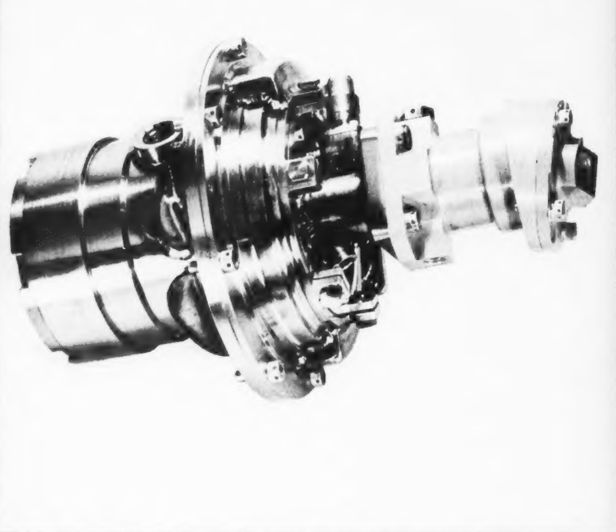
Schreiber, Raemer E., Nuclear Rockets—Los Alamos Project Rover, *Nucleonics,* Vol. 16, No. 7, pp. 70–72, July 1958.

Schreiber, Raemer E., *Nuclear-Rocket Propulsion Program at Los Alamos,* ARS 13th Annual Meeting, N.Y., Nov. 1958.

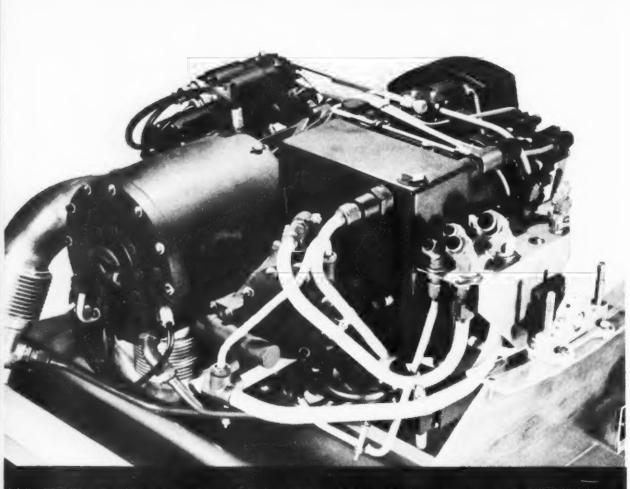
Shepherd, L. R. and Cleaver, A. V., The Atomic Rocket, *Journal of the British Interplanetary Soc.,* Vol. 7, pp. 185–194, 234–241, 1948; Vol. 8, pp. 23–27, 59–70, 1949.

Tsien, H. S., *Rocket and Other Thermal Jets Using Nuclear Energy, with a General Discussion on the Use of Porous Pile Materials,* MIT Nuclear Sci. and Eng. Seminars LIV and LV, May 13 and 15, 1947, NP-156, 25 pp.

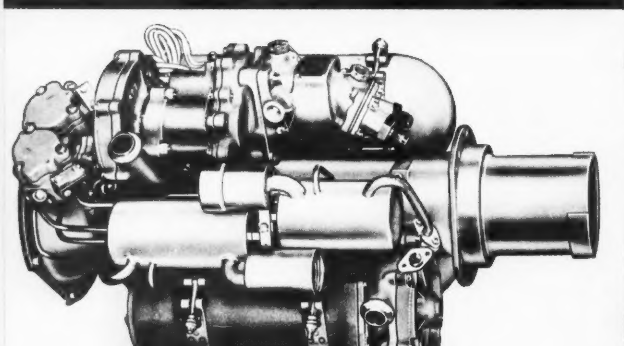
◆◆



New TAPCO-developed UNIPUMP is a solid-fuel, self-regulating, single-shaft turbo-hydraulic supply. Capacities from 1 to 5 gpm at 3000 psi for durations up to 3 minutes.



This TAPCO Auxiliary Power Unit, driven by a 4-stage solid-fueled turbine, produces 70 HP to generate 40 kva. of electricity and to drive a hydraulic pump for actuating controls.



Liquid fuel self-contained electrical and hydraulic power supply designed and developed by TAPCO. Solid fuel versions of these auxiliary power supply units are being used in Terrier missiles.

FROM TAPCO...

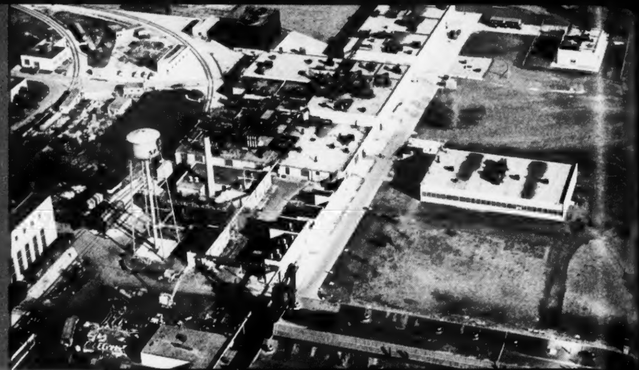
Secondary Power Systems using any energy source for any power output

Here you see a few of the secondary power systems developed and built by TAPCO for leading missile and aircraft manufacturers. These systems provide power for flight control and generate electrical energy with precisely-controlled frequencies as low as ±.001%.

Some TAPCO secondary power systems operate in high-temperature ambients. Others operate in the cryogenic range. Our half-century of experience in producing precision components to function reliably in abnormal ambients is especially important in

MINIAPS, a new TAPCO-developed solid-fuel miniature turbo generator provides up to 200 watts of power. This multiple output concept supplies precise voltages and frequencies, in both AC and DC current for missile fuzing and telemetering applications.

In the TAPCO main research and test center shown here, all types of operating conditions can be simulated... high altitudes, elevated and cryogenic temperatures, high-speed rotation, hot-liquid and solid-fuel feeds, and multiple-G. Twelve other TAPCO research and test labs throughout the country augment this laboratory.



AT TAPCO...

Capabilities and Facilities to develop any Secondary Power System

Complete facilities and manpower are available in the TAPCO Group for simulation, certification and pre-delivery testing equipment built by TAPCO.

For designing and developing secondary power systems for new applications, the TAPCO Group includes stress analysts, ceramicists and metallurgists, combustion engineers, computer programmers, and a score of other talents. A new project or idea can be staffed promptly with experts from the 1250-man TAPCO engineering group.

Available to these people are complete research, development, and test facilities, with equipment ranging from a 240-circuit, 80-channel analog computer to a high-altitude environmental test chamber.

In addition, when very unusual projects require it, the research people and facilities from the TRW staff and the 11 other TRW divisions can be called on.

More than 3-million square feet of TAPCO manufacturing facilities, equipped with every type of modern precision machine tool, are available to deliver your secondary power system on-schedule.

Three TAPCO testing facilities can test any secondary power system under simulated or actual operating conditions. This assures you of ready-to-go units proved to meet your requirements.

Let us work with you and your staff on your next requirement for a secondary power system of any type. Write to:

TAPCO's 1100-acre Roanoke Test Facility can run tests involving high-G, very-high temperatures, supersonic sound, high-amplitude vibration, high-radiation, shock, and high- altitude conditions in any combination. Shown below are some of the environmental test buildings, with Rucker Centrifuge pit to handle sustained acceleration from 0 to 60 G's and package sizes up to 600 lbs.

TRW

TAPCO GROUP

Thompson Ramo Wooldridge Inc.

CLEVELAND 17, OHIO

DESIGNERS AND MANUFACTURERS OF SYSTEMS, SUBSYSTEMS AND COMPONENTS FOR THE AIRCRAFT, MISSILE, ORDNANCE, ELECTRONIC, AND NUCLEAR INDUSTRIES

ARS news

Left, John Fenn, meeting co-chairman with Ali Bulent Cambel, introduces Sir Hugh Taylor (center), president of the Woodrow Wilson Fellowship Foundation and dean emeritus of Princeton's graduate school, who gave the main address, "Progress in Science and Education," at the 3rd Biennial Gas Dynamics Symposium banquet. Right, Moody E. Prior and Ali Bulent Cambel listen attentively.

Biennial Gas Dynamics Symposium Draws Attendance of 350

Four years ago, a small band of hardy pioneers numbering a little over 100 people and spearheaded by Ali B. Cambel of Northwestern Univ., Martin Summerfield, and Andrew G. Haley, then ARS President, gathered on the Northwestern campus for the First Gas Dynamics Symposium, which had as its theme the broad area of "Aerothermochemistry."

The extent to which this field has grown in the intervening years may be judged by the fact that the third Symposium, held at Northwestern Aug. 24–26, and now a regular biennial affair, attracted a total attendance of more than 350 scientists and engineers from all over the country. Co-sponsored by ARS and Northwestern, as were the two previous meetings, this year's Symposium took as its subject "The Dynamics of Conducting Gases," with 21 papers presented at six unclassified technical sessions covering such topics as magnetofluid- and magnetogas-dynamics, plasma physics, and plasma phenomenology and applications. The papers provided a full-scale progress report on what has been accomplished to date in these areas, and on problems which are as yet unsolved.

This year's Symposium and Proceedings, to be published early next year, were dedicated to Theodore von Karman, who received a special citation from Dr. Cambel, meeting co-chairman along with John B. Fenn of Project Squid, Princeton Univ., at the opening ceremonies. Dr. von Karman also presented the first paper on the program (see page 30).

Despite a heat wave which seared Evanston during the three-day meeting, all the Symposium sessions were well-attended, and several produced heated discussions which raised the 90-degree temperature appreciably.

One of the meeting highlights was the banquet, which drew a capacity audience of more than 300. ARS Executive Secretary James J. Harford ably carried out the toastmaster duties, while Dr. Fenn provided a sparkling introduction for the guest speaker, Sir Hugh Taylor, president of the Woodrow Wilson Fellowship Foundation and Dean Emeritus of the Princeton Univ. Graduate School.

In his address, Sir Hugh looked back on his 50 yr in physical chemistry and looked ahead to the future, noting a growing need for the "pure" engineer and educational programs to provide engineers in this category.

Ably organized by Dr. Cambel, Dr. Fenn, and the other members of the meeting committee, the 1959 Gas Dynamics Symposium stands out as one of the finest ARS events of the year. Dr. Cambel's thoughtfulness in

Seated at the speaker's table during the banquet were, left to right, C. Charles Miesse, president of the ARS Chicago Section; William C. Bradford, assistant dean of faculties at Northwestern Univ.; John Fenn of Princeton Univ., director of Project Squid and co-chairman of the symposium; Sir Hugh Taylor, president of the Woodrow Wilson Fellowship Foundation, the principal speaker; James Harford, ARS executive secretary; Moody E. Prior, dean of Northwestern's graduate school; and Ali Bulent Cambel, chairman of Northwestern's department of mechanical engineering and co-chairman of the Symposium.

providing Lake Michigan for cooling-off purposes after many of the hot sessions marks a high point in looking ahead. A vote of thanks is also due Marion Cambel for her guided tour of Chicago for wives and children of Symposium attendants.

Less than this enthusiasm is due the utilitarian aspects of the Symposium. The recent rapid growth of the science of magnetofluid mechanics may be responsible for the rather heterogeneous papers and audience background of the Symposium. It is unfortunate, from the point of view of technical cohesiveness, that the original conception of having a series of review papers to cover the now voluminous subject was dropped. As a result, the general technical quality of the Symposium fell somewhat short of the caliber exhibited in previous years. Although the results will certainly be of considerable value to anyone concerned with one or more of the general topics covered, the opportunity of providing a major contribution to the advancement of the science was lost.

Also, one general comment was, that the technical content, good or bad, was largely lost to the audience because of the manner of its presentation. First, slides were too often unreadable to all but those in front rows. Second, many of the talks involved mathematical analyses, which are certainly not in themselves detrimental, but these were discussed in such detail that proper assimilation by the audience in the limited available time was practically impossible. In some instances, this practice was carried to extremes. Together with the tendency to present totally unreadable slides, it should be forcibly discouraged in future meetings of this type.

The Symposium on Dynamics of Conducting Gases consisted of six sessions which could be grouped into three general topics: Plasma particle physics, magnetofluidmechanics (continuum concept of the plasma), and applications. The introductory paper by Dr. von Karman, titled "Some Comments on Applications of Magnetofluidmechanics," included some philosophical comments on the second of these general topics, but was primarily concerned with the third. It will therefore be mentioned later.

Of the series of papers on plasma particle physics, the outstanding contributions were by W. P. Allis and S. J. Buchsbaum on "The Conductivity of an Ionized Gas in a Magnetic Field"; by H. F. Calcote, who spoke on "Relaxation Processes in Plasma"; and by I. Prigogine, who delivered an unappreciated but brilliant discussion of "The Statistical Mechanics of the Approach to Equilibrium in Gases."

The Allis & Buchsbaum paper presented a comprehensive review of the subject, treating the usual classical cases, in which conductivity is affected first by electrons only, then by electrons in the presence of stationary ions, and finally by electrons in the presence of mobile ions. The Boltzmann transport equation was used, and effects such as those caused by density gradient and departure from neutrality were also included. Calcote gave a rather complete discussion of the importance and effect of diffusion, the different processes of ion recombination, charge exchange, electron attachment, etc., on plasma relaxation characteristics; and he presented rare, and thus most welcome, experimental data.

The Prigogine paper, although it involved a mathematical treatment far too complex for adequate group presentation, described an excellent generalization of the Boltzmann-type two-body transport cognative to the complicated *n*-body problem resulting from long-range interaction in a plasma. The method used was basi-

On the calendar

1959	
Oct. 5–9	11th Annual Convention and Professional Equipment Exhibit of Audio Engineering Society, Hotel New Yorker, New York, N.Y.
Oct. 5–9	Semi-Annual Convention of Society of Motion Picture and Television Engineers, Statler-Hilton Hotel, New York, N. Y.
Oct. 6–8	Radio Interference Reduction and Electronic Compatibility Conference sponsored by Army Signal R&D Labs at Illinois Institute of Technology, Chicago.
Oct. 6–9	Int'l Symposium on High Temperature Technology, sponsored by Stanford Research Institute, at Asilomar, Calif.
Oct. 7–8	Second Advanced Propulsion Systems Symposium, jointly sponsored by AF Office of Scientific Research and Avco-Everett Research Lab, New England Mutual Hall, Boston, Mass.
Oct. 7–9	ASME-AIME Solid Fuels Conference, Cincinnati, Ohio.
Oct. 7–9	1959 National Symposium on Vacuum Technology, American Vacuum Society, Sheraton Hotel, Philadelphia.
Oct. 8–10	Meeting of American Ceramic Society Refractories Div., Bedford Springs Hotel, Bedford, Pa.
Oct. 12–14	National Electronics Conference, co-sponsored by Illinois Inst. of Tech., at Hotel Sherman, Chicago.
Oct. 13–14	National Technical Conference on "Plastics Engineering—State of the Art Today," sponsored by Society of Plastics Engineers at the Ambassador Hotel, Los Angeles.
Oct. 26–28	IRE Professional Group East Coast Conference on Aeronautical and Navigational Electronics, Lord Baltimore Hotel, Baltimore, Md.
Oct. 26–30	1959 National Conference of the Society of Photographic Scientists and Engineers, Edgewater Beach Hotel, Chicago.
Oct. 28–29	6th Annual Computer Applications Symposium, sponsored by Illinois Inst. of Tech., at Morrison Hotel, Chicago.
Oct. 28–30	Aviation Medicine Symposium sponsored by UCLA School of Medicine, Miramar Hotel, Santa Monica, Calif.
Oct. 29–30	IRE Annual Electron Devices Meeting, Shoreham Hotel, Washington, D. C.
Nov. 2–5	Combustion Institute Western States Section Fall Meeting on Chemical Equilibria and Performance of High Temperature Combustion Systems, IAS Building, 7660 Beverly Blvd., Los Angeles.
Nov. 2–5	Fall Meeting of The Metallurgical Society of American Institute of Mining, Metallurgical, and Petroleum Engineers, part of National Metal Congress, Morrison Hotel, Chicago.
Nov. 2–6	Annual Convention of Society for Nondestructive Testing, Hotel Hamilton, Chicago.
Nov. 5–6	8th Annual Instrumentation Conference sponsored by Louisiana Polytechnic Institute School of Engineering, Ruston, La.
Nov. 11–13	National Meeting of Operations Research Society, Huntington-Sheraton Hotel, Pasadena, Calif.
Nov. 16–20	**ARS 14th Annual Meeting and Astronautical Exposition, Washington, D.C.**
Nov. 16–20	5th Int'l Automation Exposition and Congress, N.Y. Trade Show Bldg., New York, N.Y.
Nov. 18–20	Aircraft Hydraulic Conference sponsored by Vickers Inc., Park Shelton Hotel, Detroit.
Nov. 23–24	Symposium on Solid State Devices, sponsored by ISA, AIEE, IRE, Benjamin Franklin Hotel, Philadelphia.
1960	
Jan. 11–13	6th National Symposium on Reliability and Quality Control in Electronics at Washington, D.C., sponsored by American Society for Quality Control, IRE, AIEE, and EIA.
Jan. 25–29	Symposium on Stress Measurement Methods, sponsored by *Strain Gage Readings* journal, Arizona State Univ., Tempe, Ariz.
Jan. 28–29	**ARS Solid Propellants Conference, Princeton Univ., Princeton, N.J.**
Feb. 1–5	ISA Instrument-Automation Conference and Exhibit, Houston Coliseum, Houston, Tex.

cally that of applying perturbation techniques to the equations of quantum mechanics in order to solve the otherwise impossible problem in classical mechanics—an interesting reversal of the usual order of events. The author applied his method to the direct solution of several classical examples of irreversible processes, including that of the evolution of a plasma.

The series of papers treating the plasma as a conducting *fluid* (a field of study which nowadays goes under one of a number of ponderous labels, e.g., magnetohydrodynamics, hydromagnetics, magnetogasdynamics, magnetofluiddynamics, etc.) was beautifully introduced by von Karman's comparison of this "new" science with the existing techniques of ordinary fluid mechanics (see page 30).

The outstanding paper of this group—and possibly of the entire Symposium—was "Some Solutions of the Macroscopic Equations of Magnetohydrodynamics" by W. R. Sears. This was a refreshingly clear analytical treatment of several aspects of the somewhat oversimplified case of an incompressible, nonviscous, conducting fluid in a magnetic field, using the methods of conventional fluid mechanics to linearize the equations. In the first class of flows treated, small-perturbation theory was used to calculate the flow around slender bodies, the results showing both the surprisingly large effect of finite conductivity and the *very* interesting results that the "wake" propagates *upstream* in "sub-Alfvenic" flow (corresponding to subsonic flow in ordinary aerodynamics). The second case was that of the boundary-layer approximation, the results for sub-Alfvenic flow again indicating that the ordinary fluid-mechanics situation is reversed; that is, the boundary layer grows *thinner* with downstream distance, giving rise to an upstream "wake." These conclusions, although obtained using a somewhat oversimplified model, appear sufficiently interesting to be subjected to early experimental test. Finally, Sears treated the case using the more general formulation of Ohm's law, in which electron collisions are considered, demonstrating this effect in the classical example of the flow past a wavy wall. Another paper in this group, by R. A. Gross and C. L. Eisen, presented numerical data on "Some Properties of a Hydrogen Plasma" over wide ranges of pressure and temperature.

The final group of papers, dealing with some applications of plasma physics and magnetofluidmechanics, was well introduced by von Karman's summarization of the specific fields for application in the three general areas of flow modification, plasma contain-

ment, and propulsion. Although it would be difficult to select a truly outstanding paper from this group, a number of interesting ideas were presented, worthy of some brief mention.

"Applied Magnetohydrodynamics at Avco-Everett Research Laboratories," by M. Camac and C. S. Janes, summarized both theoretical and experimental research in the fields of propulsion, lift and re-entry drag devices, electrical power generation in plasmas, and very-high-temperature shock processes. W. H. Bostick and collaborators presented results of some additional experiments on their "plasmoids" in a paper titled "Experimental Study of Plasma Dynamics." This time the Bostick group utilized an electromagnetic "brake" to study the extraction of electric power from plasmas, as well as plasmoid properties such as ion density, electron density, Hall electric field, etc.

Papers by A. E. Kunen and W. McIlroy ("The Electrical Pinch Effect for Space Propulsion") and by R. V. Hess and K. Thom ("Plasma Acceleration by Guided Microwaves") both presented interesting propulsion schemes. Kunen and McIlroy utilized an ordinary pinch discharge in a tube of ingenious geometry oriented so that the "pinched" gas was driven out the end of the tube to provide thrust. Some experimental characteristics of their pinch discharges indicated good agreement with predicted results. The Hess-Thom paper departed from this general group in that it did *not* include experimental results. The authors discussed the acceleration of a plasma by the radiation pressure of high-energy microwaves in a "wave-guide accelerator." Although judgment must be withtheld pending the collection of experimental data, this method appears to be capable of producing extremely high I_{sp}.

One final paper, which presented a rather complete picture of the design, operating problems, and achievements of plasma-generating "hardware," was "Techniques for Producing Plasma Jets" by J. A. Browning. This was well received as a well-organized description of the engineering approach to plasma generation.

One concluding remark of some importance is that, with the exception of the group of papers just described and the one or two others which were specifically mentioned earlier, *practically no experimental data were presented.* It is surprising and somewhat disappointing that at this comparatively advanced date in such a popular field, so few organizations have been able to gather data of sufficient caliber to warrant presentation at a major meeting of specialists of this type.

—**Irwin Hersey and Jerry Grey**

Next Month – ARS 14th Annual Meeting And Astronautical Exposition

A year of astronautics in the making approaches in the form of the ARS 14th Annual Meeting and Astronautical Exposition to be held next month, Nov. 16–20, at the Sheraton Park Hotel in Washington, D.C. The 14th Annual Meeting will present over 30 technical sessions, some 130 papers, and more than 60 displays of the industry's progress and products, in the Astronautical Exposition.

Highlighting the Honors Night Dinner, on Wednesday, Nov. 18, will be the presentation of ARS awards, and an address by the Hon. John A. McCone, Chairman of the AEC, on "The Influence of Nuclear Technology on Rockets and Spaceflight." Complementary classified technical sessions the day following will cover recent advances in nuclear propulsion and propulsion systems.

The chart below shows the general schedule of meeting sessions and subjects. The Man-in-Space session the evening of Monday, Nov. 16, offers both papers and a seminar on the latest advances in human factors, and relates to sessions earlier in the day on physics of the atmosphere and space and bio-instrumentation in space research vehicles. Sessions on exotic propulsion systems, space communications, near-space effects on materials, space-vehicle design, and astrodynamics reflect the advancing frontier of astronautics in new fields and disciplines.

A major session on philosophy of education and the third Eastern Regional Student Conference underscore the Society's concern with education and the development of professional goals and standards with students. There will be no registration fee, by the way, for nonmember students attending only the Eastern Regional. Regular registration for students and military personnel will be $1.00, as usual.

Registration for classified sessions must be made *before* Oct. 20 with the forms mailed to each member last month. The Office of Naval Research sponsors the classified sessions this year, and clearance forms go to ONR (Code 810) filled out according to instructions.

With this exciting program, and the latest displays of the Astronautical Ex-

ARS 14th Annual Meeting Schedule

	Monday Nov. 16	Tuesday Nov. 17	Wednesday Nov. 18	Thursday Nov. 19
9:00 a.m.	Guidance	Safety & Reliability of Liquid Rockets	Structures & Materials in Near Space	Space Law & Sociology
	Physics of the Atmosphere & Space	Astrodynamics	Current Problems of Space Travel	Power Systems
	Wave Phenomena	Far Space Communications Techniques	Test Facilities & Ground Support Equipment	*STUDENT CONFERENCE*
		Space Law & Sociology	Advances in Miniaturization	
9:30 a.m.	Section Delegates Conference		Survey of Storable Propellants & Combustion Oscillations *(Confidential)*	Recent Advances in Nuclear Propulsion *(Secret)*
12:30 p.m.	Luncheon	Luncheon	Luncheon	Luncheon
2:30 p.m.	Ion Propulsion	Solid Rockets	Plasma Propulsion	Power Systems
	Bio-Instrumentation	Space Communications Equipment	Recoverable Boosters	
	Propellants & Combustion	Philosophy of Education	Payload Instrumentation	Recent Advances in Nuclear Propulsion *(Secret)*
		Ramjets *(Confidential)*	Liquid Rockets *(Confidential)*	
7:00 p.m.			BANQUET	
8:00 p.m.	Man-in Space	NATIONAL CAPITAL SECTION PROGRAM		

position, the ARS 14th Annual Meeting should prove an occasion not to miss.

Two More Companies Become ARS Members

Two more companies have become corporate members of the AMERICAN ROCKET SOCIETY. The companies, their areas of activity, and those named to represent them in Society activities are:

Aluminum Company of America, Pittsburgh, Pa., engaged in manufacture of rocket engine cases, solid propellant metal additives, and missile structural members. Named to represent the company in ARS are Wm. C. Woodward, manager, Aircraft & Missile Sales; W. D. Mathers, manager, Forgings Sales; D. M. Guy Jr., sales development engineer; J. Paul Lyle, assistant chief, Fabr. Metallurgy Div.; and J. F. Faulkner, manager, aircraft & missiles section of Sales Development Div.

Nems-Clarke Co., Silver Spring, Md., manufacturer of telemetry receiving equipment. Representing the company in ARS activities are A. S. Clarke, president; G. S. Vermilyea, executive vice-president; R. E. Grimm, director of engineering; J. F. Whitehead, director of sales; and K. B. Redding, assistant director of sales.

ARS Announces 1960 Student Awards Competition

Each year, the AMERICAN ROCKET SOCIETY offers undergraduate and graduate students an opportunity to gain recognition for original work through its $1000 ARS Chrysler Corporation (undergraduate) and $1000 ARS Thiokol Chemical Corporation (graduate) Awards. Students, individually or in teams, compete for these awards by submitting papers on any subject of their choosing related to astronautics.

Now is the time to get forms giving complete details on eligibility and procedures for this competition. Write for forms to the following address, specifying the award you wish to compete for: 1960 Student Awards Competition, AMERICAN ROCKET SOCIETY, 500 5th Ave., New York 36, N. Y.

The deadline for submitting papers in the competition is Sept. 1, 1960. The two awards will be presented at the ARS Honors Night Dinner to be held on Dec. 7, 1960, in the Shoreham Hotel, Washington, D. C.

ARS Paper Deadlines

Date	Meeting	Location	*Deadline
1959			
Nov. 16–20	14th Annual Meeting	Washington, D.C.	Past
1960			
Jan. 28–29	Solid Propellants Conference	Princeton Univ.	Nov. 30
March 23–25	Ground Support Equipment Conference	Detroit, Mich.	Feb. 1
April 6–8	Structures and Materials Conference	Santa Barbara, Calif.	Feb. 23
May 9–12	ARS Semi-Annual Meeting and Astronautical Exposition	Los Angeles, Calif.	March 21
May 23–25	National Telemetering Conference	Santa Monica, Calif.	April 1
Aug. 15–20	11th International Astronautical Congress	Stockholm, Sweden	June 15
Dec. 5–8	ARS Annual Meeting and Astronautical Exposition	Washington, D.C.	Oct. 19

*For reviewed and approved manuscripts in the New York office. Subtract 30 days for unsolicited papers that must go through the reviewing procedure and 60 days for abstracts submitted for consideration. Send all papers and abstracts to Meetings Manager, ARS, 500 Fifth Ave., New York 36, N.Y.

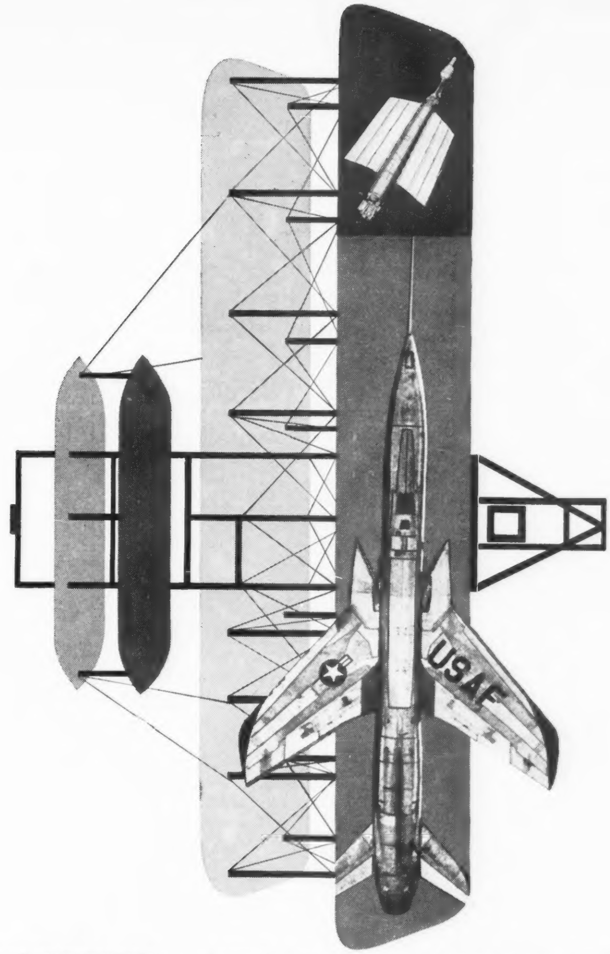
SECTIONS

Antelope Valley: At its Third Annual Dinner Dance, held in June at the Edwards AFB NCO Club, the Section elected these new officers: Richard J. Harer, president; Hugh E. Coyer, vice-president; Robert C. Rowlin, First Lt., USAF, secretary; and Theodore A. Sundahl, treasurer (re-elected). Outgoing officers were the following: Walter A. Detjen, president; Robert E. Cundiff, vice-president; Palmer L. Long, secretary; and Theodore A. Sundahl, treasurer.

The first Section meeting after the installation of new officers was an August dinner meeting at Aleck's Restaurant in Lancaster, Calif. After a "happy hour" and an excellent buffet, some 50 husbands and wives heard **Walter Kuehnegger** speak on the Reaction Control Simulator, which represents one method of preparing man for spaceflight. Currently being investigated by Martin-Denver, the simulator consists of a 10-ft sphere of a light material supported by a cushion of air. This air cushion permits the simulator to assume any desired altitude by the thrust of compressed-air reaction jets. Dr. Kuehnegger's very interesting talk was followed by a long and lively question-and-answer period.

Husbands and wives again attended the September dinner meeting, and heard guest **John Harrison** of Convair-Astronautics discuss countdown operations for both missiles and such transitional aircraft as the experimental X-15. This talk gave a little deeper picture of the much-discussed business of launching complex vehicles. The dinner meeting, incidently, provided a congenial occasion to welcome and introduce personnel now arriving at the Edwards AFB Directorate of Rocket Propulsion and Missiles from the Propulsion Laboratory of WADC, Dayton, Ohio.

The second number of the Section's


USAF

Northern California Section Visits NASA-Ames

Top, H. Julian Allen, chief of the High Speed Research Div., welcomes fellow members and guests of the Northern California Section at their recent dinner meeting and tour of the NASA Ames Research Center, Moffett Field, Calif. Seated at the head table, from left, are Bernard Ellis, Howard Kindsvater, C. F. Hansen, A. J. Eggers, and Chris Wilder. Center, the dinner drew a capacity crowd at Ames' cafeteria. Bottom, A. C. Charters, head of the Hypervelocity Ballistics Range, explains a hypervelocity helium-drive gun to one touring party.

quarterly news bulletin, "Rocket Topics," which has received much favorable comment, is now out, and the Section is looking forward to a more ambitious version of the bulletin for the future.

As noted in the latest "Rocket Topics," the Section will meet jointly with local sections of IAS and SETP on Oct. 29 to hear guest speaker **Carlo R. Tosti,** Col., USAF, special asst. to the commander of ARDC, present a comprehensive review of present and future ARDC projects, including industrial planning.

—Richard J. Harer

Chicago: The Chicago Section inaugurated a monthly news letter, "Spacetronautics," and prepared for a busy season, which had an auspicious beginning last month with a visit and address by ARS President **John P. Stapp,** who gave an illustrated talk on the Astronauts. The second meeting of the season for the Section is scheduled for the 23rd of this month, and features as guest speaker **Wilfred Roth,** director of the Roth Laboratory for Physical Research, Hartford, Conn.

National Capital: DOD is conducting over 60 different projects designed to meet the "rising threat" of Russian ballistic missiles. Former ARS president **George P. Sutton,** newly appointed chief scientist of ARPA, revealed this information at the first summer meeting of the Section in July. He also described some of the projects, and hinted at others. The warhead for Minuteman, for example, may be doubled thanks to recent developments in solid propellants, he said.

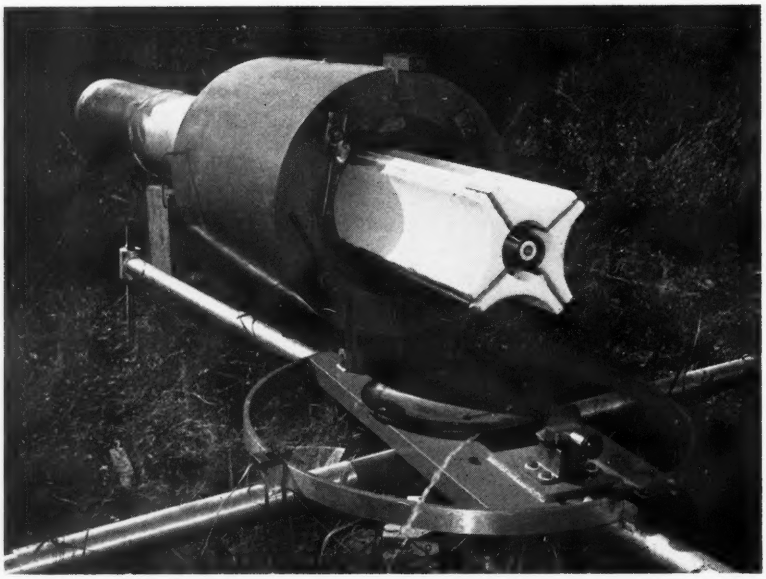
A series of major projects, according to the ARPA chief scientist, is concerned with trying to distinguish between ICBM's and decoys. He says this accounts for new devices being built to analyze radiations emitted by various objects traveling at high speed through the atmosphere.

—S. David Pursglove

Northern California: A capacity crowd of 126 members and guests, including many wives, attended the July dinner meeting, held at the NASA Ames Research Center, Moffett Field, Calif., and more than 80 other members and guests showed up later to take in a guided tour of five of Ames' facilities—an experimental model of an arc jet used to produce high-velocity gas streams; the Hypervelocity Ballistics Range, in which models of space vehicles are launched from guns at extreme speeds into various gases; the Atmosphere-Entry Simulator, in which models are launched at high speed into a wind tunnel; the Physics Laboratory, which features an ion-beam accelerator, used to study molecular bombardment of solids and gases, and a monster shock tube, constructed from a 16-in. naval gun and two 6-in. guns, driven by combustion of hydrogen and oxygen gases in helium; and the world's largest wind tunnel—40 by 80 ft in cross-section—which is used to study vertical-takeoff aircraft and methods of safely landing supersonic manned vehicles. This was an outstandingly successful and enjoyable meeting, thanks to the courtesy and enthusiasm of the people at Ames who made it possible.

—Frederick Hansen

Southern California: At a classified meeting of the Section in July, held at the IAS Building in Los Angeles, **S. K. Hoffman,** vice-president and general manager of Rocketdyne, and a past president of the Southern California Section, gave an informative and stimulating discussion of "Development Aspects of the 1,000,000-lb-Thrust Liquid Propellant Rocket Engine." He gave background information about this engine, which is so important to prospective spaceflight projects, and outlined Rocketdyne's development work on it. The talk, illustrated with slides and movies, stimu-



Atlantic Research Birthday

Atlantic Research Corp. celebrated a decade of success by moving into new headquarters near Washington, D.C., accepting an award from the Navy, and preparing to turn out rockets like its Arcas, shown above in specially developed breach-loading launcher operable by one man.

lated many questions from the members.

—Eric Burgess

Utah: Members and guests of the Section had the unusual pleasure of hearing ARS President **John P. Stapp** address them at the August dinner meeting. Col. Stapp described and discussed the biomedical research providing background and directly contributing to the man-in-space program and the coming era of extraterrestrial exploration. His stimulating and informative presentation was received with enthusiasm.

—Joseph H. McKenna

STUDENT CHAPTERS

Parks College: At the final meeting of the academic year in July, the Chapter heard guest **Peter W. Soule,** a professor at Parks, discuss "Lunar Impacts." His was a most informative talk, covering both the basic mathematical theory involved in sending orbital and impact vehicles to the moon and the tremendous engineering problems to be overcome.

The members of the Chapter look forward to the coming year with the expectation that it will be the finest to date.

—Norbert J. Kulpa

CORPORATE MEMBERS

American Electronics Co. has entered an agreement with Marquette Mfg. Co. to cooperatively market a new "voltage sensitive trigger" device for use as a storage battery automatic charging controller . . . **Atlantic Research Corp.** has received a Certificate of Commendation from Navy BuOrd for the firm's technical advancement of solid-propellant rocket technology. . . **Sylvania Electronic Products** is purchasing a 25,000-sq-ft plant at Manchester, N.H., for manufacture of transistors and plans to expand production of refractory metals . . . **Thompson Ramo Wooldridge** is building a $2 million plant in Anaheim, Calif., for the West Coast Div. of its Tapco Group. . . Construction has begun of **Union Carbide's** Research Institute at Eastview, N.Y.

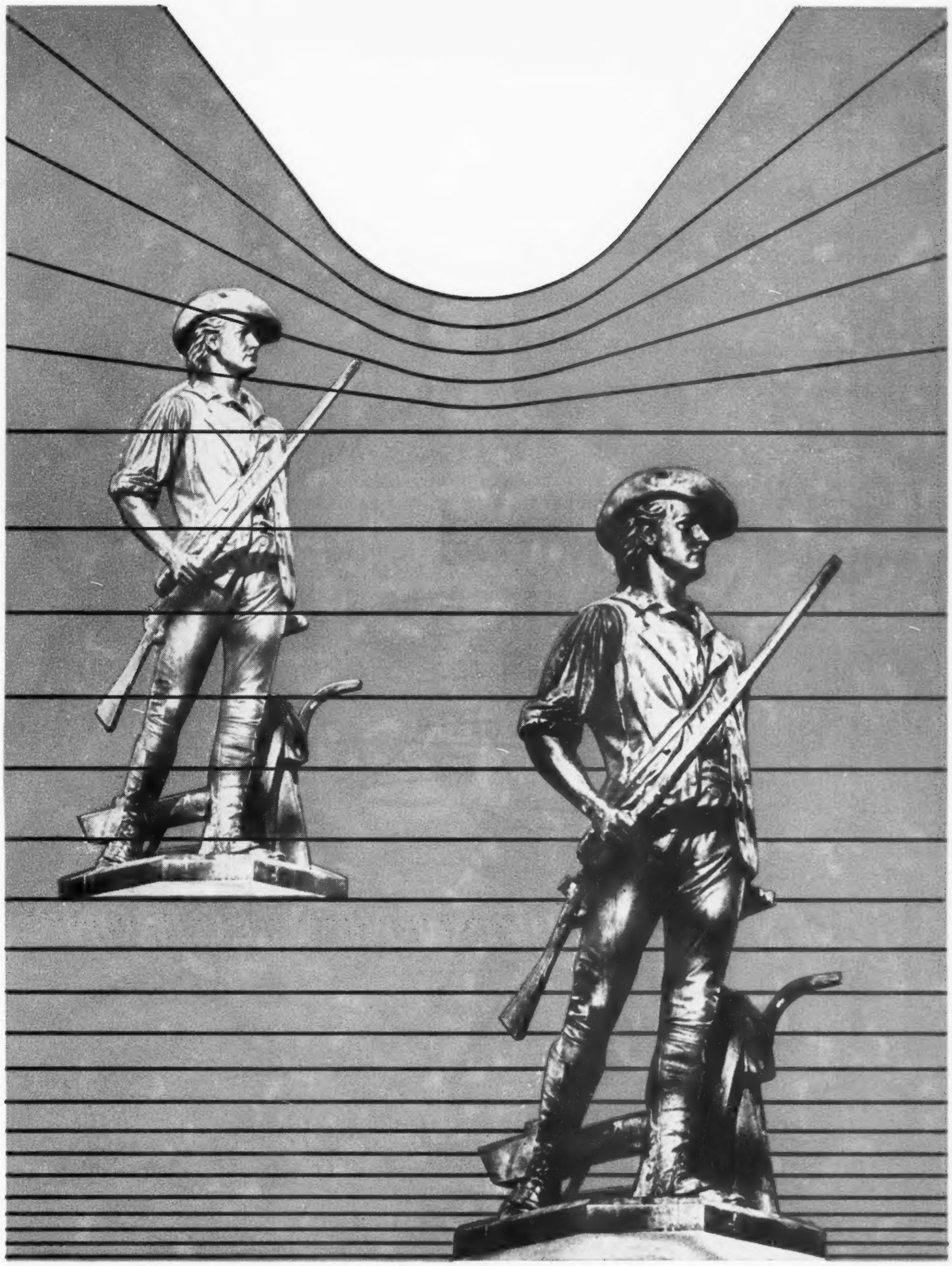
TECHNICAL COMMITTEES

Flight Mechanics: Samuel Herrick, professor of the Dept. of Astronomy at the Univ. of California has been appointed chairman of the ARS Flight Mechanics Committee. Named by Prof. Herrick to serve on the committee are: R. M. L. Baker Jr., Aeronutronic Systems; Richard B. Dow, Air Force Office of Scientific Research; W. B. Klemperer, Douglas Aircraft; Hans Lieske, Rand Corp.; Angelo Miele, Purdue Univ.; Eugene Rabe, Cincinnati Observatory; Robert E. Roberson, Systems Corp. of America; Joseph Siry, NASA; Louis Vargo, Aeronutronic Systems; and Lynn E. Wolaver, WADC.

Herrick

ARPA Chief Scientist Addresses National Section

At a summer luncheon meeting, the National Capital Section heard of recent DOD programs on ballistic missile defense from George P. Sutton, chief scientist of ARPA and past ARS president, shown (left) at the head table chatting with Milton Rosen, chief of NASA's rocket-vehicle development program, and (right) addressing the well-attended function, with William Roennau, vice-president of the Section, listening attentively.

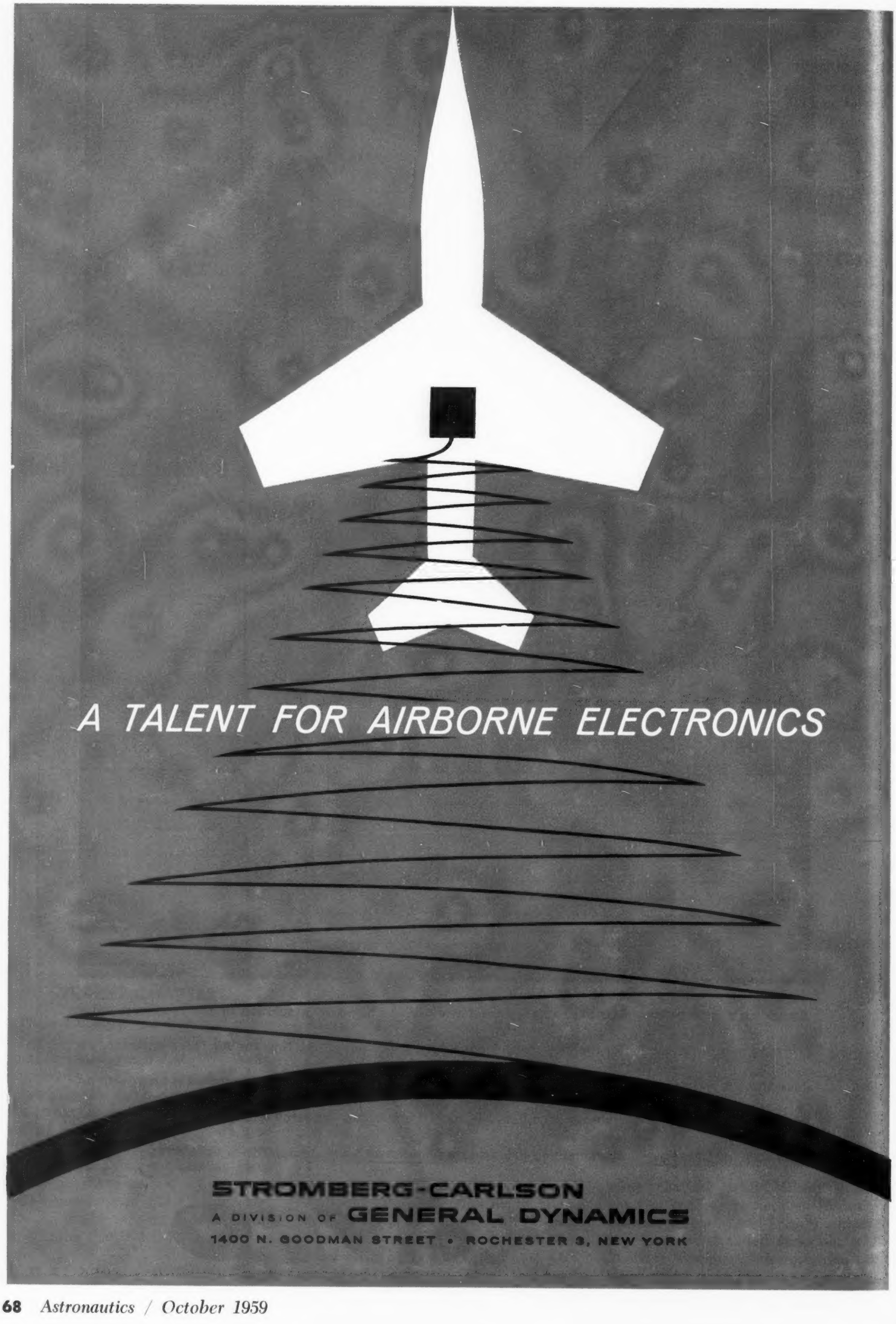


Avco and a Modern Minuteman—Recent work at Avco led to a solution of the missile re-entry problem, and to production of the nose cone for the Air Force Titan ICBM. Now the Air Force announces a development program for Minuteman, a solid fuel missile that will be capable of instantaneous firing with no preparatory fueling delays. Its nose cone, too, will come from Avco's Research and Advanced Development and Lycoming Divisions . . . implementing this modern Minuteman's vigilant defense of our shores.

UNUSUAL CAREER OPPORTUNITIES FOR QUALIFIED SCIENTISTS AND ENGINEERS . . . WRITE AVCO TODAY.

Avco

AVCO MAKES THINGS BETTER FOR AMERICA / AVCO CORPORATION / 750 THIRD AVENUE, NEW YORK 17, N. Y.


A TALENT FOR AIRBORNE ELECTRONICS
STROMBERG-CARLSON
A DIVISION OF GENERAL DYNAMICS
1400 N. GOODMAN STREET • ROCHESTER 3, NEW YORK

Photon Rocket Propulsion

(CONTINUED FROM PAGE 36)

electromagnetic radiation concentrated within a parallel beam, a total momentum, P, is carried by this beam ($P = \Sigma p = \Sigma E/c = c\Sigma m$) and the reactive force or thrust exerted by this beam is $F = dP/dt = L/c = c(dM/dt)$, where F = thrust, L = total power contained in beam, and dM/dt = rate of conversion of mass into radiant energy. Note that these relations are independent of the frequency of the radiation.

If a source of radiation, a searchlight for example, produces thrust at an exhaust velocity of c = 300,000,000 m/sec, why should it not be used as a rocket motor? The answer is simply that our present-day technologies do not permit more than an extremely small portion (γM) of the rocket fuel mass (M) to be transformed into radiant energy. If we put a flashlight somewhere in outer space and switched on its light beam, it would represent a photon rocket. However, by the time its supply of energy was exhausted, it would have reached a final velocity of only 10^{-4} m/sec, and its total mass would have been reduced by a fraction of only 10^{-11}, which would make it utterly impracticable as a rocket vehicle.

This demonstrates a fact which is sometimes overlooked when photon propulsion is discussed: It is not only the exhaust velocity, but also the *useful mass ratio*, which characterizes a rocket vehicle. While the former is excellent in photon rockets, the latter is still hopelessly small. Whether we will ever succeed in developing techniques for the conversion of matter into radiant energy at a conversion factor which makes photon rockets useful, is a speculation which exceeds the scope of this paper.

Even though the technical realization of a photon rocket is still beyond our conception, the theory of the flight-mechanical behavior of such rockets can be developed on the assumption that certain technical problems are solved. E. Saenger, much to his credit, analyzed the features of this photonic propulsion in a series of brilliant papers, a compilation of which is listed at the end of this discussion.

Photon rockets transform their fuel mass by means of a hypothetical conversion process into radiant energy according to Einstein's equation, $E = Mc^2$. The radiation, consisting of photons, is collimated by a mirror or other suitable device and emitted as a parallel beam. While the thrust of a chemical rocket motor is given by $F_{ch} = \dot{M}v$, where $\dot{M}$ = rate of mass consumption and v = exhaust velocity of combustion products, the thrust of the photon rocket is $F_{ph} = \dot{M}c$.

Comparison of these two equations shows that for the same thrust the mass consumption of the photon rocket is smaller by a factor of $v/c \approx 10^{-5}$. For this reason, photon rockets can reach end velocities which are considerably greater than those of chemical rockets. In fact, end velocities of photon rockets may approach light velocity to such an extent that the usual laws of classical mechanics lose their validity and must be replaced by the laws of the relativity theory. The "ideal" photon rocket converts its fuel completely into radiation, and emits the radiation in a collimated beam without losses.

Another type of photon rocket converts only a certain fraction, γ, of its fuel mass, M, into radiation. The rest, $(1 - \gamma)M$, is left over from the conversion process as waste and drops from the rocket without contributing to the thrust. These "partial" photon rockets deserve consideration because their technical realization may be easier than that of the "ideal" photon rocket, although they are, of course, less efficient.

A third type is no longer a real photon rocket. Its fuel is again partially converted into energy. However, this energy is not emitted in the form of photons, but is further converted into kinetic energy of the waste products. The rocket emits particles at an exhaust velocity $v < c$, and v depends essentially upon the conversion factor, γ. As γ approaches 1, the exhaust velocity approaches c, and for $\gamma = 1$ this rocket is an "ideal" photon rocket.

This third type is particularly interesting because it covers chemical, nuclear, plasma, ion, and photon rockets alike. If we assume that the conversion of the energy back into kinetic energy of the exhaust particles works without losses (an assumption not justified with present technology), we find the following conversion factors for the transformation of mass into kinetic energy:

Type	Conversion factor (mass → energy)
Chemical	5×10^{-11}
Plasma	5×10^{-10}
Ion	5×10^{-8}
Nuclear	
Fission	10^{-3}
Fusion	4×10^{-3}
Ideal photon	1

For the nuclear transformations, it is assumed that the entire amount of fuel consists of fissionable or fusionable

material, and that the fission or fusion energy is transformed entirely into kinetic energy of the fission or fusion products. No working fluid is used. Techniques for this process are still completely unknown.

The flight-mechanical performance of rockets whose end velocity is a noticeable fraction of light velocity must be computed with equations derived from relativistic formulas. (All flight-mechanical considerations are made under the assumption that the vehicles move in a space without atmosphere and gravity fields.) Starting from the well-known Lorentz transformations, we find that the velocity increment du of a vehicle under the influence of a rocket motor is not independent of the velocity, u, which the vehicle already has with respect to the coordinate system in which it began its flight. Instead of the classical momentum equation, $\bar{M}du = -vdM$, where $\bar{M}$ = instantaneous mass, du = velocity increment, v = exhaust velocity, and $-dM$ = mass decrement, we must write:

$$\bar{M}\frac{du}{1 - u^2/c^2} = -vdM$$

where u = instantaneous velocity with respect to an observer at rest. Integration yields the following expression (for derivation see any of the first five suggested additional readings at the end of this article):

$$\frac{M_0}{M_1} = \left(\frac{1 + u_1/c}{1 - u_1/c}\right)^{c/2v}$$

where M_0 = mass at time $t = 0$, M_1 = mass at time $t = t_1$, and u_1 = velocity at time $t = t_1$.

If the transition, u_1/c approaches zero, is made, this equation reduces readily to Tsiolkovskii's well-known rocket equation: $M_0/M_1 = e^{u_1/v}$.

The integrated expression displayed above was derived in 1946 by J. Ackeret and, in a somewhat modified form, by R. Esnault-Pelterie as early as 1930. H. G. L. Krause proved in 1955 that this equation is valid for a constant thrust as well as for a constant acceleration. A further interesting discussion of the integrated expression is given by I. M. J. Kooy. The Suggested Additional Reading lists key work by these authors.

In the case of an ideal photon rocket, where $v \rightarrow c$, this integrated expression transforms into

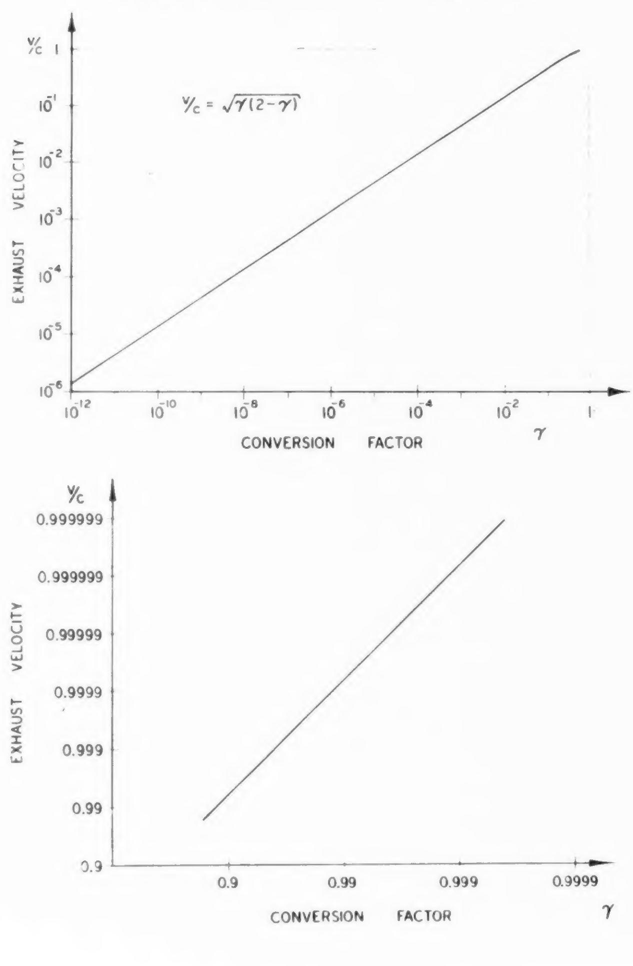
$$M_0/M_1 = \sqrt{(1 + u_1/c)/(1 - u_1/c)}$$

or, with $M_0/M_1 = \mu$, into $u_1/c = \mu^2 - 1/\mu^2 + 1$.

The graph on page 36 shows the untransformed integrated equation for M_0/M_1 in graphic form, with the end velocity plotted as u_1/c versus the mass ratio, $\mu = M_0/M_1$. The exhaust velocity, v, was chosen as parameter. The curve farthest to the left represents chemical rockets (v = 3000 m/sec); the curve farthest to the right, the ideal photon rocket ($v = c = 3 \times 10^8$ m/sec.)

This graph shows that unless the mass ratio is unrealistically high, only the ideal photon rocket, or a particle rocket with an exhaust velocity very close to light velocity, can reach an end velocity approaching the velocity of light. Even an energy source like nuclear fusion is far from providing end velocities near that of light.

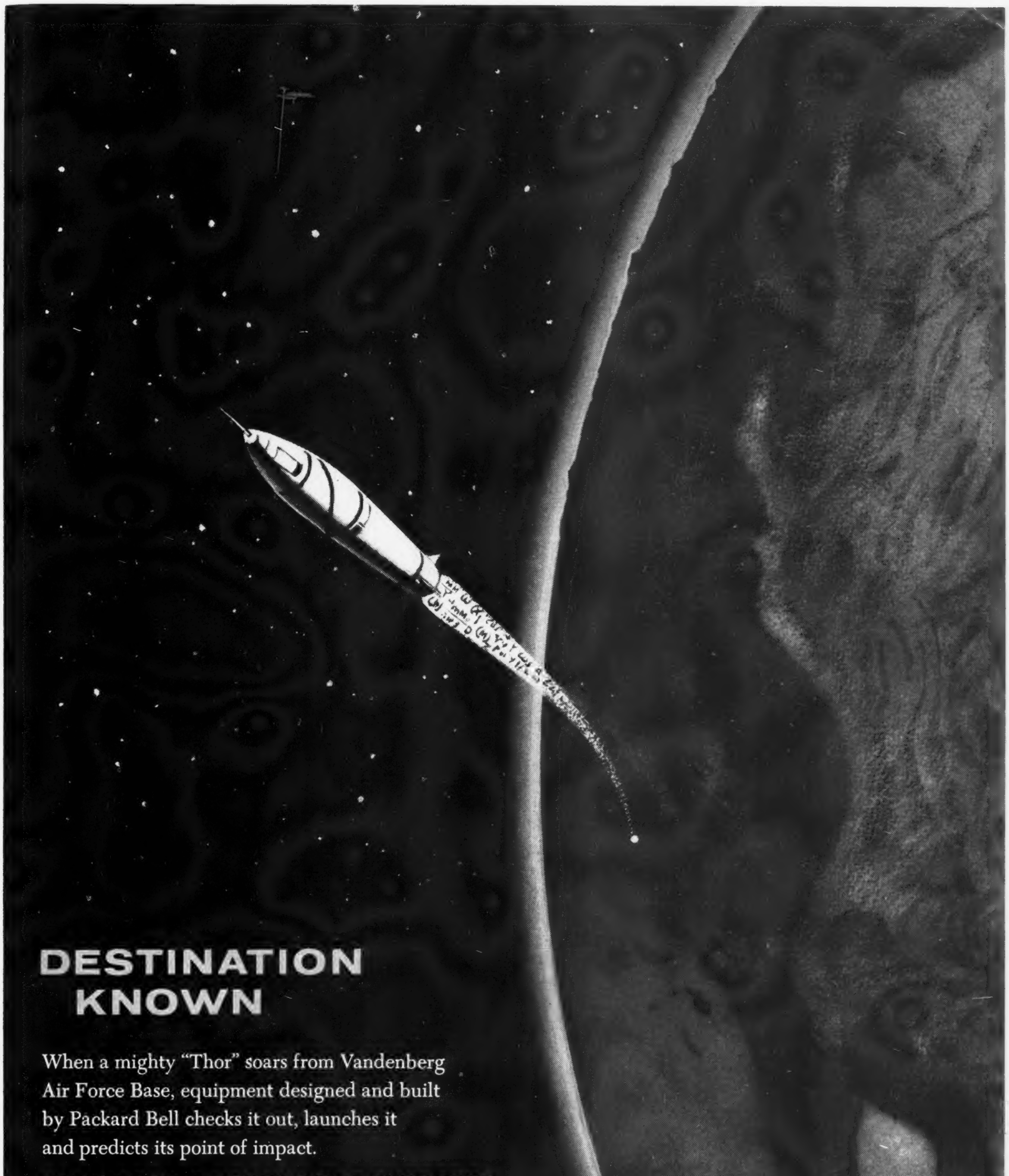
Saenger's Expression Shown Graphically



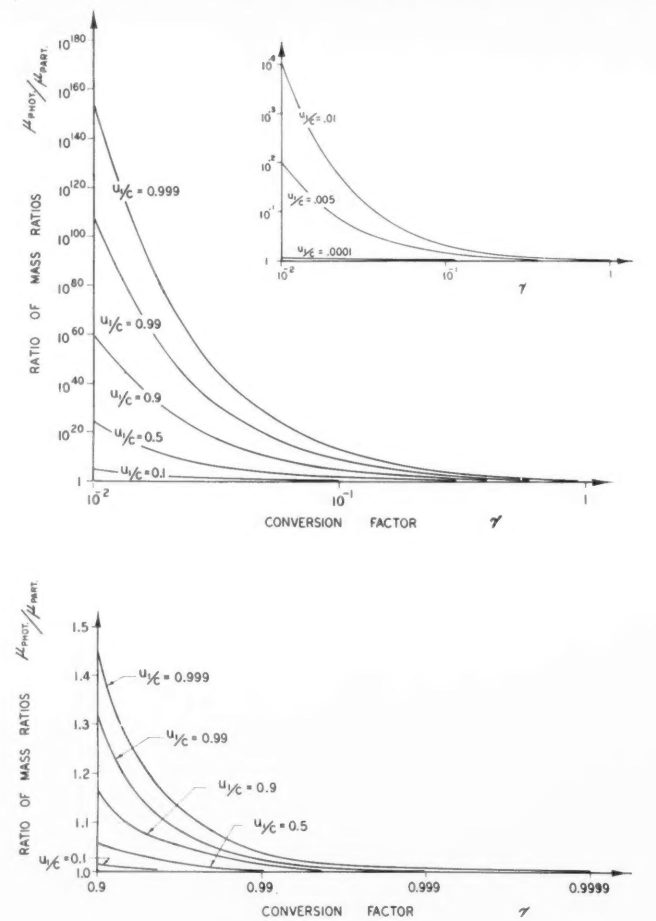
Conversion Process

If we assume a hypothetical conversion process which first transforms the fraction, γM, of the fuel mass into energy, and then applies this energy to accelerate the residual fuel mass, $(1 - \gamma)M$, we obtain a particle propulsion system described above as type 3. Most interestingly, the exhaust velocity of the propellant particles is only a function of the conversion factor (γ) and is independent of the nature of the fuel or burning time. The relation between conversion factor (γ) and exhaust velocity (v), derived by Saenger, is given by $v = c\sqrt{2\gamma - \gamma^2}$. It is assumed here that no losses occur during the energy conversion processes. For an ideal photon rocket, $\gamma = 1$ and $v = c$.

The two related plots at left show Saenger's expression graphically. The upper part shows the exhaust velocity in the form v/c as a function of the conversion factor (γ) from


DESTINATION KNOWN
When a mighty "Thor" soars from Vandenberg Air Force Base, equipment designed and built by Packard Bell checks it out, launches it and predicts its point of impact.
ENGINEERING BEYOND THE EXPECTED
The Missile Impact Predictor is one-eighth the size and was built at one-tenth the cost of previous systems. Ground support equipment matches the reliability built into the "Thor." All combine to guarantee an effective weapon for retaliation or space exploration... destination known.
PACKARD BELL ELECTRONICS
Technical Products Division
12333 W. Olympic Blvd.
Los Angeles 64, Calif. · BR. 2-6141

Particle and Photon Propulsion Compared Through Mass Ratio



$\gamma = 10^{-12}$ to $\gamma = 0.8$; in the lower part, v/c is plotted versus γ for the range $\gamma = 0.8$ to $\gamma = 0.9999$. If 0.999 of the fuel mass were converted into energy and applied as kinetic energy to the residual 0.001 of the original fuel mass, the latter would be ejected at a velocity equal to 0.9999995 c.

Of particular interest is the end velocity which the rocket vehicle would reach with this kind of a particle propulsion system, and with a given mass ratio. Since there is a direct relationship between v and γ in Saenger's expression, the right side of Saenger's expression can be substituted in the integrated form of the equation for mass ratio shown above, and the parameter in the graph on page 36 can be read in terms of γ as well as in terms of v. The γ values are plotted in this graph beside the v values. A similar diagram has been given by T. Foelsche, who pointed out the great significance of the conversion factor for the end velocity.

Now compare two rocket propulsion systems, both having the same conversion factor. The first system is a "partial photon rocket" that transforms the mass (γM) into photons and drops the residual $(\gamma - 1)M$. The second system converts the same mass (γM) into kinetic energy of the residual $(\gamma - 1)M$; it is a "particle rocket." For the same γ and the same end velocity u_1, their mass ratios $(\mu = M_0/M_1)$ will be different. The ratio, $\mu_{\text{photon}}/\mu_{\text{particle}}$, under these conditions takes the following form if $\gamma \rightarrow 1$, $\mu_{\text{photon}}/\mu_{\text{particle}} \rightarrow 1$ as expected:

$$\frac{\mu_{\text{photon}}}{\mu_{\text{particle}}} = \left(\frac{1 + {}^{u}1/c}{1 - {}^{u}1/c}\right)\frac{1 - \sqrt{2/\gamma - 1}}{2\sqrt{2\gamma - \gamma^2}}.$$

The graphs shown above plot this equation with the end velocity $({}^{u}1/c)$ as parameter. The upper part shows conversion factors from 10^{-4} to 0.8 versus the ratio of the mass ratios, $\mu_{\text{photon}}/\mu_{\text{particle}}$ in the lower part, conversion factors from 0.8 to 0.999 are plotted versus the ratio, $\mu_{\text{photon}}/\mu_{\text{particle}}$.

The graphs indicate that for all $\gamma < 1$, the particle rocket is superior to the partial photon rocket, because it will reach the same end velocity with a smaller mass ratio. A photon rocket is efficient only when the total amount of fuel is converted entirely into photons.

These simple relations are valid only as long as no losses occur during the conversion process. The influence of conversion losses is described in detail by Saenger. In essence, they result in greater mass ratios than indicated in the graph on page 36. Deviations from the ideal curves are particularly noticeable at end velocities near light velocity.

A numerical example will illustrate the dimensions and performance data of an ideal photon rocket, a partial photon rocket, and a particle rocket.

50-Ton-Payload Terms

Let the "empty mass" M, of the vehicle be 50 tons, including structures, energy-conversion plant, and crew facilities; and let the desired end velocity be $u_1/c = 0.9$. The total time of propulsion, at constant thrust, is assumed to be 1 yr. The graph atop page 76 indicates that the initial mass of an ideal photon rocket would be 217.5 tons. The conversion of 167.5 tons of fuel into photons during a period of 1 yr would represent a power output of the photon thrust chamber of 4.75×10^8 MW, as compared to a total electric power production of the world in 1957 of 3.5×10^5 MW.

Assuming now a conversion factor of $\gamma = 0.5$ for a "partial photon rocket," we find an initial mass of 940 tons, and a power output of the thrust chamber of 1.26×10^9 MW.

The "particle rocket," again with 50 per cent of its fuel transformed into energy, would start with an initial mass of 272 tons, and a power output of its particle thrust chamber of 3.15 $\times 10^8$ MW.

The most powerful chemical thrust chamber presently in use in this country has a power output of about 5×10^3 MW for a period of a few minutes.

These examples may give an impression of the technical difficulties encountered when the desired end velocity approaches the velocity of light. But, even at $u_1/c = 0.9$, the time dilatation which characterizes relativistic flight is not yet impressive.

With an acceleration time of 1 yr, the travel time to the nearest fixed star, Alpha Centauri, and back to earth is almost 10 yr as measured on

earth; during the same period, the travelers will age by about 7 yr. The time-dilatation effect, which causes the travelers to age more slowly than those staying at home, may be expressed as the ratio of the duration of a space trip as measured by the travelers aboard the vehicle to the duration of the same trip as measured from the earth. The trip may start and end on earth, or start on earth and end on or near another planet or star.

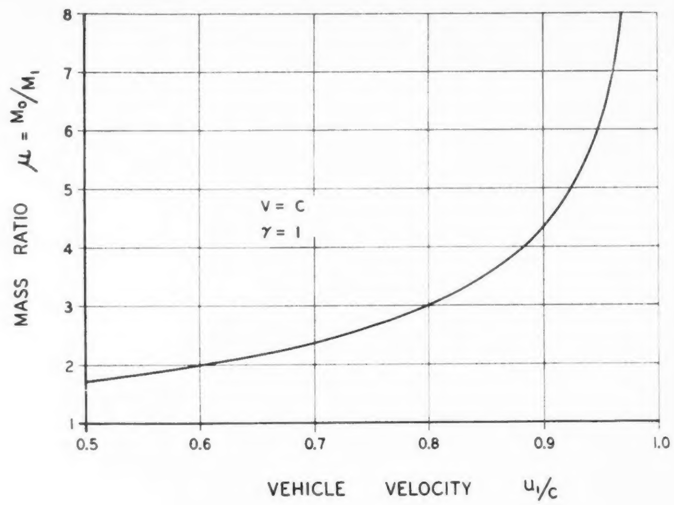
Two Specific Cases

Consider two specific cases. In Case I, the vehicle accelerates during a time which is small in comparison to the duration of the whole trip, and reaches a constant velocity u_1. At the end of the trip, it decelerates during a time which is again negligible with respect to the entire duration of flight.

In Case II, the ship accelerates continuously in such a way that its acceleration, as measured on board the vehicle with a normal spring-mass accelerometer, is constant. Upon reaching the midpoint of the voyage with the velocity, u_1, a continuous deceleration of the same amount is applied until the vehicle arrives at its target at zero velocity.

The time dilatation factors for these two cases as functions of the end velocity u_1/c are plotted in the graph shown below. Even a relatively modest time dilatation factor of 100 can be reached only when the end velocity of the velocity differs from light velocity by less than 10^{-4} in Case I, and by less than 10^{-6} in Case II. An ideal photon rocket could achieve a velocity of $c(1 - 10^{-4})$ with a mass ratio (M_0/M_1) of 140 or a velocity of $c(1 - 10^{-6})$ with a mass ratio of 1400. A particle rocket with a conversion factor of $\gamma = 0.5$ would require a mass ratio of 300 to reach a velocity of $c(1 - 10^{-4})$ and a mass ratio of 4400 to reach $c(1 - 10^{-6})$.

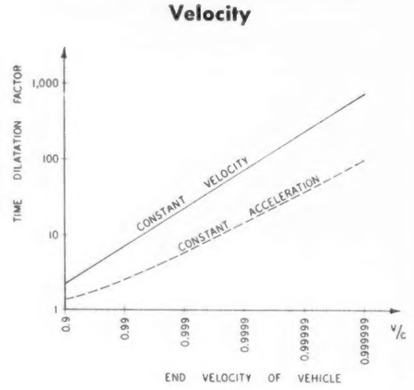
Mass Ratio Versus End Velocity of Ideal Photon Rocket



A conventional chemical rocket converts 5×10^{-11} of its propellant mass (M) into energy; this energy raises the temperature of the remaining $(1 - 5 \times 10^{-11})\ M$ to about 3000 K. If the energy released in a fission reactor were used only to heat the fission products, their temperature would rise to about 10^{10} K. A hypothetical rocket engine with a conversion factor of 0.5 would raise the temperature of the residual fuel to the order of 10^{13} K, if the energy were used to heat the fuel.

It is obvious that temperatures of this order cannot be handled within a thrust chamber built on the basis of present technologies. If the energy became available in another form, its conversion into kinetic energy of the unidirectional exhaust particles would, with any one of the energy conversion processes known today, only work with an efficiency of < 1. Even the small portion of energy which is unavoidably transformed into heat would suffice to make heat problems within the conversion device unsurmountable.

Onset of Time Dilatation with Velocity

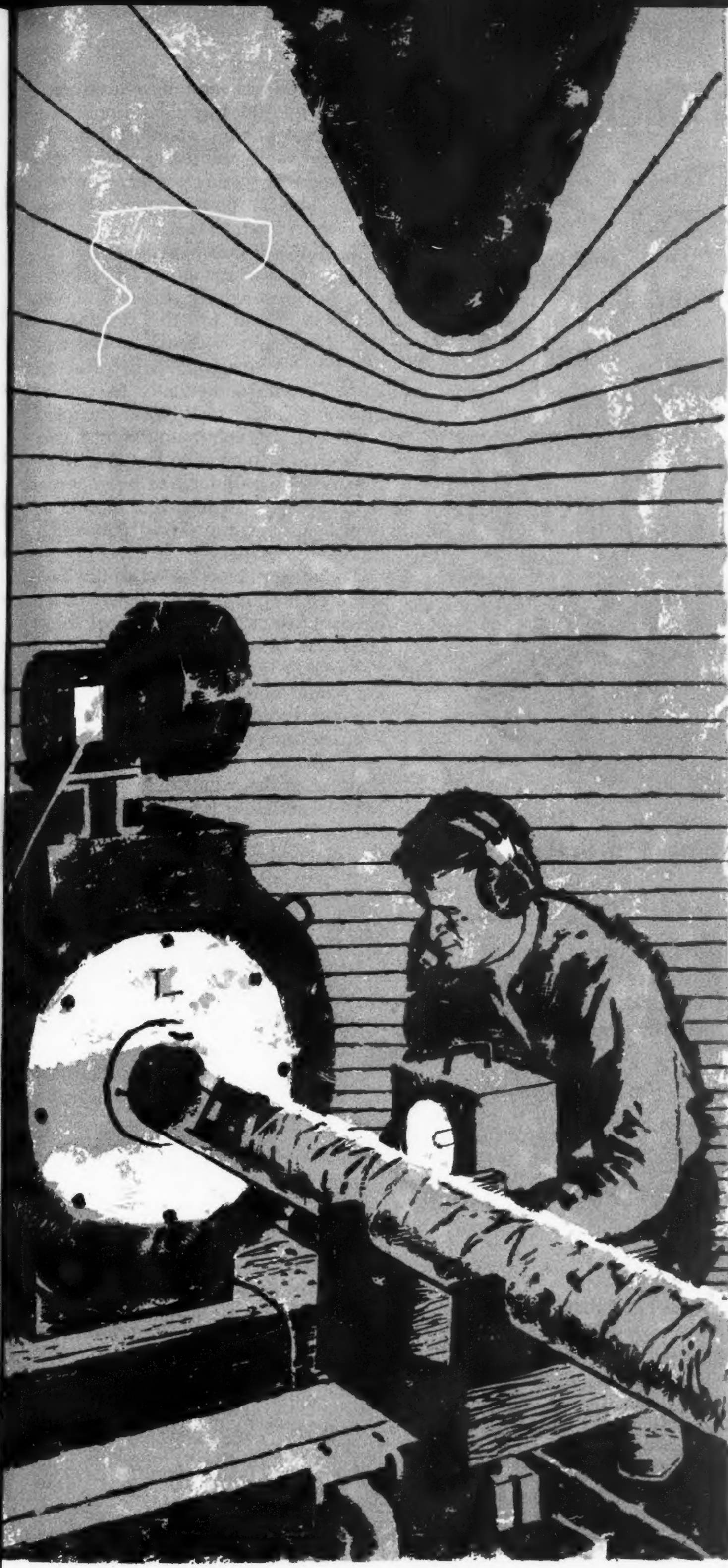


A direct conversion of mass into radiant energy, as it is known from the annihilation of electrons and positrons, requires a store of "antiparticles." However, antiparticles are distinguished by their nonstability; their lifetimes count only in microseconds. Even if the problems of storage and controlled consumption were solved, the problem of collimating the annihilation radiation would still exist. Most of the quanta from annihilation processes have energies of the order of mev's, and therefore are extremely difficult to reflect or collimate. And yet, the collimating device must have an efficiency better than about $(1 - 10^{-7})$ or the energy absorbed by the collimator would vaporize the vehicle immediately. No way of solving this problem is presently known.

The only way to reach even the nearest fixed stars during the life span of a man is by means of a rocket system that converts at least about 2 per cent of its fuel mass into energy and expels the remainder of its fuel by means of this energy.

The lowest mass ratio would be obtained by the "ideal" photon rocket that converts its fuel completely into radiating energy (photons). As soon as the conversion factor is smaller than one, a "particle" rocket, which uses the energy from the conversion to eject the nonconverted remainder of the fuel, is more efficient.

Even if the energy of a nuclear fusion reactor could be transformed completely into kinetic energy of the


L

fusion products, and if a mass ratio of at least 100:1 could be achieved, this rocket engine would still not be sufficient for a round trip to the nearest fixed star during the lifespan of a man. This is true for any conceivable kind of nuclear reaction.

The highest possible conversion factor of a nuclear reaction (a hypothetical reaction in which protons and neutrons are fused together to form a medium-weight nucleus) is less than 10^{-2}. No methods are presently known even theoretically to convert mass into energy on a large, controlled scale with a greater conversion factor.

Even at a conversion factor of 10^{-2}, the energy would have to be imparted to the exhaust particles in a form other than heat energy to avoid unbearably high temperatures.

The ideal photon rocket would have a power output from its thrust chamber surpassing that of chemical thrust chambers by a factor of 10^5, referred to the same thrust. Regenerative cooling would not be possible because of the small rate of fuel consumption. Conversion device, container walls, and reflecting surfaces would have to be ideal to the extent that they would not absorb more than about 10^{-7} of the total power passing through the thrust chamber.

We are left with the conclusion that photonic propulsion and relativistic rocket mechanics present an extremely interesting field for the theoretician, but that a number of practical limitations will prevent the realization of photon rockets until entirely new methods of energy conversion and high-temperature technologies have been found.

Suggested Additional Reading

Saenger, E., Zur Theorie der Photonenraketen, *4. Int. Astron. Congress*, Zurich, 1953. Oldenbourg R., *Zur Mechanik der Photonenstrahlantriebe*, Muenchen, 1956.

Ackeret, J., *Helvet. Physica Acta* 19, 103, 1946. *J. Brit. Interpl. Soc.* 6, 116, 1947. *Interavia* 11, 989, 1956.

Esnault-Pelterie, R., *L'Astronautique* (Paris), 229, 1930.

Krause, H. G. L., *Astronautica Acta II*, 30, 1956.

Kooy, I. M. J., *Astronautica Acta IV*, 31, 1958.

Foelsche, T., AFMDC-TR-59-4, *ASTIA Doc.* AD 209328, Holloman AFB, 1959. AFMDC-TN-59-8, *ASTIA Doc.* AD 214006, Holloman AFB, 1959.

Huth, J. H., *Rand Report* P-1479, 1958.

Huth, J. H., Augenstein, B. W., and Holbrook, R. D., *Rand Report* RM 2194, 1958. ♦♦

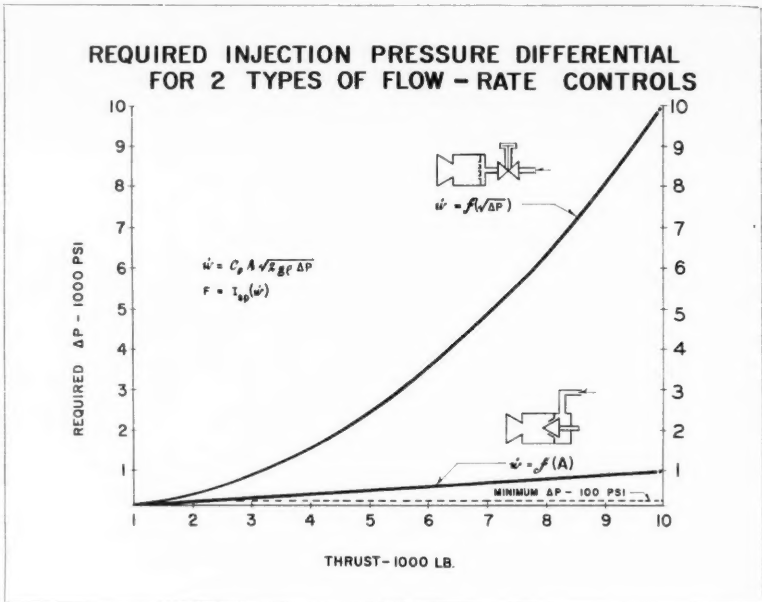
Variable-Thrust Engines

(CONTINUED FROM PAGE 41)

show the elements of the injection system developed by NOTS for variable-thrust control. Here, variable-area injection is accomplished by means of a single moving part within the injector.

In the top drawing, the injector is in the closed position, and the chamber is at zero thrust level. The fuel and oxidizer are restrained from entering the chamber by a cylindrical annular pintle, which is held against the stationary conical faces of the injector body and the central core. The pintle is held tightly against these seats by hydraulic pressure. Releasing this pressure allows the springs within the injector to retract the pintle, opening annular passages for the fuel and oxidizer and permitting them to enter the combustion chamber.

By varying the hydraulic pressure, it is possible to obtain any desired injection area for zero to the full-rated thrust of the engine. This injection system is also readily adaptable to many methods of actuation other than hydraulic control, such as direct electrical operation of the pintle by torque motor or magneto striction.



To gain long engine operation, regenerative cooling is employed in all engines with greater than 100-lb thrust. The drawing on page 41 shows a NOTS variable-thrust engine, rated at 3500-lb maximum thrust, with regenerative cooling. Both fuel and oxidizer are used regeneratively to obtain the greatest cooling capacity for the engine.

It is in the area of regenerative cooling that one of the major problems in

variable-thrust engine design lies. As thrust is reduced by reducing propellant flow rate, the cooling capacity is correspondingly reduced, but the conditions within the chamber remain much more constant, and the heat load is not reduced proportionately. Thus, at some point thrust is reduced, and there is no longer sufficient heat capacity in the flowing propellants to cool the chamber sufficiently. In engines with approximately a 3000-lb-thrust level, this point is reached at about 20 per cent of rated full thrust. In larger engines, which have greater heat capacity in the propellants at full rate of thrust, the crossover point is a much smaller percentage of full thrust.

Pintle-Design Influences

By proper design of the pintle shape, the mixture ratio at any thrust level can be determined. It is possible to use this feature to solve the problem of engine cooling at very low thrust levels by designing the injector to shift mixture ratios as the lower thrust levels are approached, and thus depress the flame temperatures to acceptable limits. Although this solution results in a corresponding loss in performance at the lower thrust levels, the loss occurs at the lowest propellant flow rates, so that the average performance of the engine over its entire thrust range remains high.

For many applications, this simple method is satisfactory. However, studies are being made of alternative methods of engine cooling—such as by fluid films and transpiration—that would be divorced from variations in propellant flow rate.

A limited effort is being directed toward obtaining a variable-area nozzle that would aid in the development of a constant-chamber-pressure engine for low-altitude applications, where the variation in nozzle thrust coefficient, with corresponding degradation of engine performance, would justify the added complexity of such a system. However, most of the foreseeable applications of this engine are at altitudes greater than 40,000 ft and do not require this added complexity to assure good performance.

Only a few applications of variable-thrust engines can be described here. Studies of air-to-air missile systems, particularly those using infrared guidance, show that such missiles are limited in speed due to aerodynamic heating. To achieve the highest kill probability and to ensure the greatest separation of the launching aircraft from the effects of warhead explosion, the missile should be boosted quickly to the maximum tolerable velocity in order to proceed at this velocity to the target. Because it is unrealistic to impose restrictions on either the launching-aircraft velocity or altitude, the missile must have a range of thrust variation of the order of 35:1.

Vector and roll control of a missile may also be obtained with variable-thrust engines. This is accomplished either by using multiple variable-thrust engines for the main propulsion system or by using small variable-thrust vector motors. Small vector motors are not restricted to liquid-propellant systems. Rather, they offer a simple, reliable method of controlling any large vehicle when they are installed as separate guidance packages. Such a package complete with liquid propellants shows a considerable gain in weight and simplicity over jetevators, swiveled nozzles, and other similar methods of achieving control through main-thrust deflection.

Because maneuvering in outer space requires a direct application of the action-reaction principle, it is in this field that precisely controllable, variable-thrust engines become indispensable. Variable-thrust motors can be used to control satellite position and orientation in space. Precise, circular orbits of satellites can be attained by radio-controlled engines whose thrust magnitude and duration can be commanded by ground stations. A space vehicle such as an antisatellite missile could be similarly maneuvered to meet another orbiting object in space.

The ability to maneuver is a requirement of any sophisticated manned space vehicle, and the use of controlled thrust to decelerate and safely land space vehicles on the moon is an obvious application of variable-thrust engines. For such applications, the basic engine designs are now off-the-shelf items, and the nation's future in space has been brought one step nearer. ◆◆

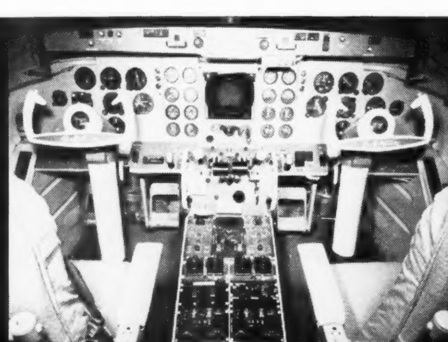
Flying Laboratories

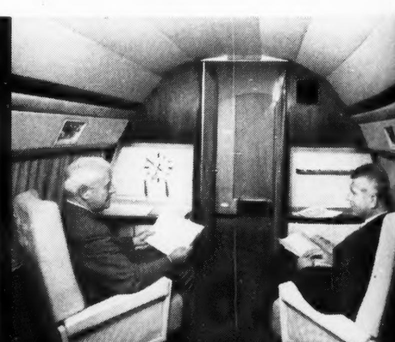
The Army Signal Corps now has at its command six aircraft, equipped by Collins Radio's subsidiary Alpha Corp., capable of testing and evaluating virtually any combination of electronic systems. The aircraft employ five independently operating navigational systems—VOR, lf and hf ADF, TACAN, and LORAN.

Map of the Moon

GE offers free of charge a large and technically accurate map of the moon showing all major landscapes charted geographically. Write Missile and Space Vehicle Dept., Rm 4C, 3198 Chestnut St., Philadelphia 4, Pa.

YOU ARE INVITED to inspect the airplane at one of the following distributors: Atlantic Aviation, Wilmington, Delaware; Southwest Airmotive, Dallas, Texas; Pacific Airmotive, Burbank, California; and Timmins Aviation, Montreal, Canada.





Hybrid Propulsion Systems

(CONTINUED FROM PAGE 43)

accomplished by a high-pressure gas bottle or a suitable gas generator.

Besides high performance, hybrid propulsion also offers a number of features important for ease of construction and safety and durability in handling and storage. These are:

1. *Containment of high-temperature reactions.* Perhaps the most important advantage is that the high-temperature reaction is confined to a rather small area where insulation by graphite or similar materials and regenerative cooling by the oxidizer are practical. Consequently, it becomes possible to consider much higher temperatures in ordinary construction materials than would be practical without liquid cooling.

2. *Mechanical properties of the fuel charge.* A second important feature is that the solid fuel can have a very low oxidizer content, so the charge (or grain) can have the high strength and resilience needed to avoid the familiar problems of creep and cracking.

3. *Safety by separation of fuel and oxidizer.* The low oxidizer content of the solid fuel and the separate packaging of the main oxidizer contribute significantly to the safety that is attainable in manufacturing and handling. For some high-energy systems, the fuel and oxidizer combinations are safe even when they are in contact. As an example, some of the propellant combinations under current investigation have been placed in contact and no reaction has been apparent over a period of several days. This contact safety feature has been demonstrated for systems delivering impulses as high as 260 sec, but it should not be considered a universal characteristic, particularly for some of the more energetic reactants.

4. *Storage capability.* Finally, many promising high-energy hybrid systems should be capable of long-term storage over wide ranges of temperatures (—100 to 500 F) and provide instant readiness without field maintenance. Cure problems for a fuel-rich solid charge should be essentially nonexistent with proper compounding, and certainly a solid charge of pressed metal should withstand storage and handling with very little difficulty. Storability of oxidizers, such as nitric acid, in lightweight flight-type tanks has already been demonstrated by actual tests covering periods of over 5 yr at ambient temperature, over 1 yr at 165 F, and several days at temperatures up to 500 F. Instant readiness comparable with that of well-established in-service, solid-propellant rockets has also been demonstrated.

Radical scaling up of an established design should be relatively straightforward. For a given burning time, very large units could be constructed rather simply from multiple fuel charges, thus avoiding the necessity of developing a complicated grain design. The liquid component would simply require larger tanks for the increased fuel capacity. Construction costs of large units (5000-lb total weight or greater) should be generally comparable with costs of existing solid-propellant engines.

The simplicity attainable in hybrid propulsion engines of large size using thrust-direction control is illustrated by the design on page 43. This design also shows the efficiency with which available space may be used for volume-limited situations. The liquid-oxidizer tank surrounds most of the nozzle assembly. Because the tank is both cool and at low pressure, it can be made to conform closely to the allowable dimensions without adding excessive inert weight. Thrust-direction and roll control in this design are achieved by thrust regulation through oxidizer control to the four nozzles canted slightly outward.

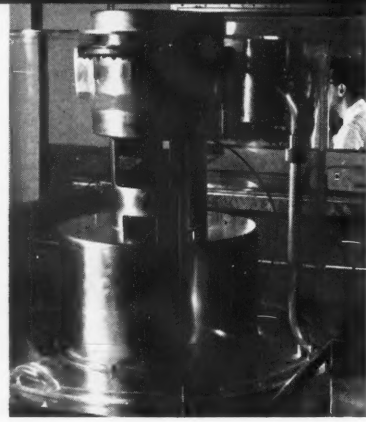
In a comparative-weapon-analysis program for a volume-limited application, this design, using a hybrid combination already demonstrated, achieved approximately 30 per cent greater range than did the best conventional propulsion system that could be developed within one year. ◆◆

Research Reactor For Walter Reed AMC

Atomics International, Div. of North American Aviation, has designed a 50,000-watt reactor for Walter Reed Army Medical Center in Washington, D.C., which will be used for biological research and medical treatment. A unique feature will be an area below the reactor where high-intensity gamma rays essentially free of neutrons can be directed on an experiment. The reactor will be built in about a year.

Propellant Safety Seminar

Members of government, military, and industrial groups gathered in seminar recently, under the auspices of the Armed Services Safety Board, at the Naval Propellant Plant, Indian Head, Md., to discuss safety in handling high-energy propellants during both research and manufacturing operations.



Republic's Plasma Engine

This laboratory model of a magnetic-pinch plasma engine represents part of Republic Aviation's recently announced astronautics program.

Magnetofluidmechanics

(CONTINUED FROM PAGE 30)

lines in a two-dimensional supersonic flow is extended to a great variety of wave phenomena. For example, the sonic circle, which we use in the case of a uniformly moving perturbation source in order to determine the direction of the Mach lines, is replaced by an odd diagram consisting of several pieces which serve as possible envelopes of characteristics. Each system of characteristics corresponds to another mode of wave propagation. For certain cases, we even encounter the odd phenomenon that the wave lines, instead of following the object moving through the fluid, are forward-directed, i.e., they run before the object which creates them.

Thus magnetofluidmechanics can be considered as *an ideal intellectual playground for aerodynamicists.* However, let us not forget that fluid mechanics, especially the theory of potential motion in a fluid, was until the beginning of this century essentially also an ideal playground for mathematicians. That it became a technical discipline serving the design of aircraft and propulsion devices was due to two discoveries: Those of the concept of the boundary layer and of the wing theory, started by the works of Kutta and Joukowski and further developed by Prandtl and his followers. Therefore, it appears attractive to consider what kind of practical applications we can expect for magnetofluidmechanics in the coming decades.

First, we ought to note that magnetofluidmechanics started with a practical application: Hartmann designed a magnetic pump to put mercury in motion for his experiments on the behavior of conducting fluids in a magnetic field. Even Einstein suggested the use of a liquid metal driven by a magnetic field as coolant in a refrigerator, in order to eliminate the necessity of moving parts. He considered the lubrication of moving parts in the refrigerator a problem. Unfortunately, or fortunately, for us as users of modern refrigerators, the practical engineers solved the problem of lubrication so well that the elimination of moving parts lost its importance. However, electromagnetic pumps are used by the most modern laboratories, like the Argonne National Laboratory, for pumping liquid metals.

It appears to me that practical applications of magnetofluidmechanics can be expected in three fields, which we can characterize by the terms flow modification, containment, and propulsion. We shall consider these in order.

Flow Modification. The fundamental experiments on the influence of the magnetic field on the laminar motion of a conducting fluid were made by Hartmann himself. He investigated the influence of the magnetic field on the incompressible flow corresponding to the Poiseuille flow treated in classical fluid mechanics. More recently, similar investigations were carried out for the Couette flow of a compressible conducting fluid, especially by Liepmann and Bleviss. Rossow calculated the case of an incompressible boundary layer flow along a flat plate with a magnetic field applied perpendicular to the plate. Kauzlarich and Cambel investigated the analogous flow of a compressible conducting fluid.

Magnetic Fields

All these investigations showed the theoretical possibility of changing the velocity and temperature gradients at the wall by application of magnetic fields. Nevertheless, it appears that such applications are not very promising from the practical point of view. In most cases, significant changes in drag or significant reduction of heat transfer could be achieved only by extremely high magnetic fields or by artificial increase of the conductivity, i.e., at very high magnetic Reynolds number.

The critical case of the stagnation point heat transfer was investigated by a great number of authors, mostly theoretically. However, the general result is similar to that stated above. The main result is that significant effects can only be achieved if the dimensionless quantity

$$\frac{(\text{Magnetic Reynolds Number}) \times (\text{Magnetic Pressure})}{(\text{Aerodynamic Pressure})}$$

is large. This condition requires either very high magnetic fields or a combination of moderate magnetic fields with high magnetic Reynolds number.

Containment. In the hope of releasing the energy of nuclear fusion, several methods for electromagnetically containing extremely hot ionized gases are under study. In the "magnetic mirror" and "Stellarator" concepts, the plasma is contained by externally applied magnetic fields. The pinch method utilizes the interaction of very large currents, with the magnetic fields which they generate, to compress the conducting plasma.

Both these schemes have been plagued with instabilities and energy losses, which have prevented the attainment of sufficiently high temperatures to support thermonuclear reactions.

It has also been proposed that the plasma be contained by the pressure of electromagnetic radiation.

While the attainment of thermonuclear reactions may be very difficult, the technology developed may have more immediate application. Thus, for each of these containment methods, an analogous plasma acceleration scheme has been proposed.

Propulsion. The development of propulsion devices is in full flux. Thus, in these comments, we will attempt only to present a logical classification for the various fundamental ideas.

1. *Ion propulsion,* based on the electrostatic acceleration of charged positive elementary particles. The main problems are production of ions, i.e., practical ion sources, and elimination of the electrons, i.e., neutralization of the space charge.

2. *Electrostatic acceleration of colloid-size charged particles.* Practical methods have been proposed; for example, use of colloid particles carried in the vehicle and also utilization of dust or charged particles existing in outer space.

3. *Plasma acceleration.* The principal methods can be listed as follows:

   a. Acceleration by steady, externally imposed electric and magnetic fields.

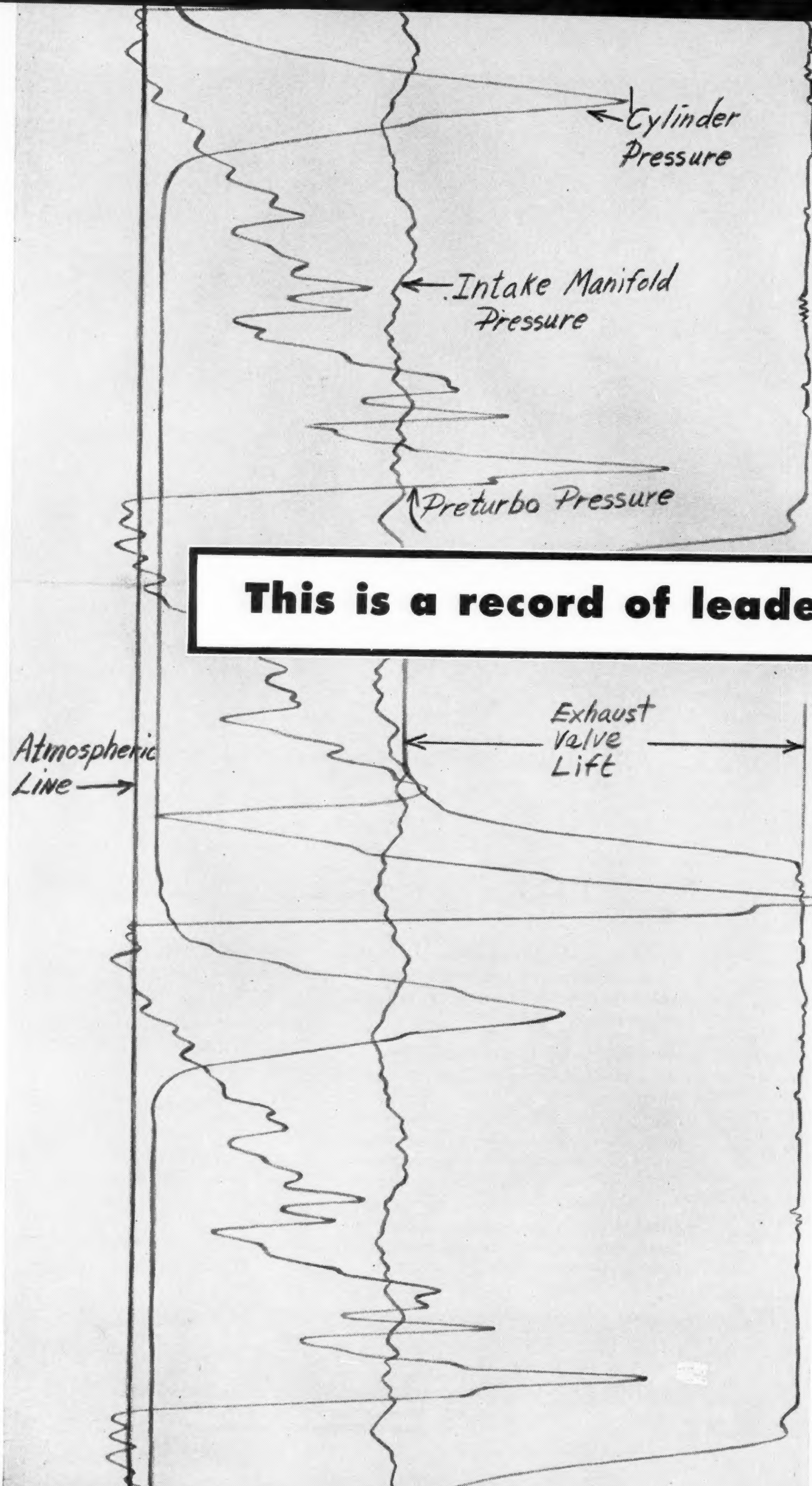
   b. Acceleration by traveling magnetic fields; this method presents the possibility of eliminating electrodes.

   c. Acceleration by interaction of currents and their magnetic fields; for example, by the Bostick rail accelerator; the T-type shock tube; and the annular-type shock tube (e.g., Patrick).

   d. Acceleration by electromagnetic pinch effect.

   e. Accerelation by externally imposed electric field, i.e., by radiation pressure.

It should also be noted that some of the schemes for direct conversion of heat into electromagnetic energy can be considered as applications of plasma physics and magnetofluidmechanics. ◆◆



This is a record of leadership in

HONEYWELL

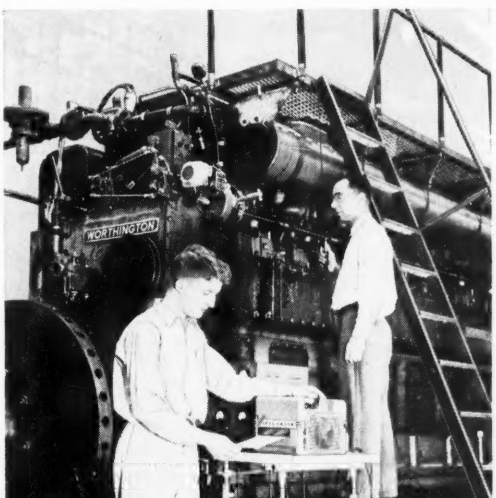
The Worthington Corporation used a Honeywell 906 Visicorder to chart the heartbeat of a Worthington Tripower diesel engine. These Tripower (oil fuel, dual fuel, or spark ignition gas) engines have a fourteen inch bore, an eighteen inch stroke, and develop more than 265 h.p. per cylinder at 450 RPM.

The Visicorder used in these tests makes a direct, instantly-readable record of the pressure variations in the exhaust manifold, cylinder, and intake manifold to determine optimum valve timing and engine configuration. The Visicorder also produces a permanent record of strain gauge measurements taken on the frame and other critical engine parts.

For the manifold and cylinder pressures, strain gauge pressure transducers and a strain gauge amplifier were used. For the valve lift patterns, a linear potentiometer powered with a small battery was connected directly to the Visicorder.

Analysis of these data has led to changes in the Tripower engine for best performance.

ip in diesel engine research



Ted Dupler (left) and John McAllister, Worthington Engine Research Engineers, measure intake manifold, cylinder, and exhaust manifold pressures and valve stroke on a Tripower with a Honeywell 906 Visicorder.

The Honeywell Visicorder is the pioneer and unquestioned leader in the field of high-frequency, high-sensitivity direct recording oscillography. In research, development and product testing everywhere, instantly-readable Visicorder records are pointing the way to new advances in product design, rocketry, computing, control, nucleonics . . . in any field where high speed variables are under study.

The new Model 906A Visicorder, now available in 8- and 14-channel models, produces longitudinal grid lines simultaneously with the dynamic traces, time lines, and trace identification by means of new accessory units.

To record high frequency variables—and monitor them as they are recorded—use the Visicorder Oscillograph. Call your nearest Minneapolis-Honeywell Industrial Sales Office for a demonstration.

Reference Data: Write for Visicorder Bulletin
Minneapolis-Honeywell Regulator Co.,
Industrial Products Group, Heiland Division
5200 E. Evans Ave., Denver 22, Colo.

Honeywell

HONEYWELL *Industrial Products Group*

Cesium-Ion Propulsion

(CONTINUED FROM PAGE 35)

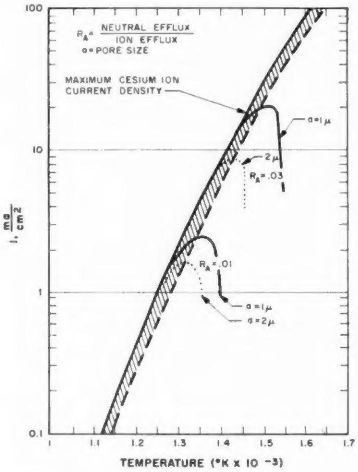
other material capable of withstanding the required temperatures, on the face of which is fastened a porous tungsten sheet. The cesium diffuses through the tungsten and comes off as ions which are accelerated by electrodes. The tungsten ionizer is contoured for good beam formation. The electrode through which the ion exit is pictured as an electron emitter (presumably thermionic) over a portion of its surface to provide electrons for neutralization of the ion exhaust. The reason for the double gap which first produces an acceleration through a potential difference $\Phi_0 + \Phi_1$ and then a deceleration through Φ_1 will be discussed later.

Tungsten is proposed as the ionizer since it is a material for which sufficient physical measurements have been made to permit detailed calculation of performance characteristics. Other materials, such as molybdenum, platinum, and tantalum, may also be satisfactory.

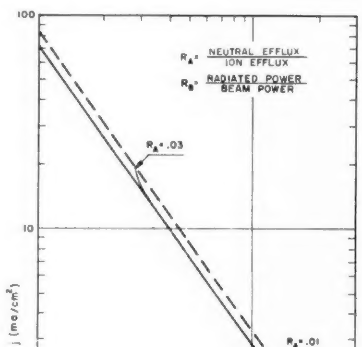
The use of a porous aggregate presents fabrication problems, and whether it is the most convenient form for the ionizer to assume needs to be considered. At first, one might propose that the ionizer be an opaque surface with cesium vapor delivered to the surface from which the ions are to be withdrawn, say, as vapor jets from the accelerating electrode. This is ruled out, because the density of cesium vapor in the interelectrode space would then be so great that there would be an excessive amount of scattering of the ions.

Ernst Stuhlinger has proposed that the cesium be injected from the side, away from the accelerating electrodes, but through an array of ribbons so oriented that no cesium vapor can get through without striking a heated surface. However, cesium striking surfaces not directly exposed to the accelerating electrode must re-evaporate as neutral cesium, because of space-charge effects. Attempts to overcome this objection by placing potential differences between successive layers of ribbons must result in a multi-energetic beam with a very difficult beam-formation problem.

With the porous aggregate, there is still the problem of neutrals evaporating from the holes. However, when the pore size gets sufficiently small, cesium will be delivered to the leading surface almost entirely by diffusion over the surface of the granules comprising the porous aggregate, rather than by transport of vapor through the holes. From data of D. B. Langmuir and J. B. Taylor, and a simplified geometrical representation of a porous material, it is possible to arrive at the information in the graph top below on current densities obtainable as a function of temperature, with R_A the material loss factor (neutral efflux/ion efflux) as parameter. This information is only for 1- and 2-micron pore sizes, and the values of R_A shown are 0.01 and 0.03, very small as far as wastage of expellant goes. However, because of ion-beam scattering, it is extremely important that very little cesium vapor be introduced into the gap; and since R_A increases very rapidly with pore size, we have not presented information on larger pore sizes.



Cesium-ion currents from the surface of porous tungsten for 1- and 2-micron pore sizes. The shaded area between the solid and broken lines defines the desired operating region.



Current density satisfying radiative power loss and accelerating voltage requirements for a 1-micron pore size tungsten ionizer.

The main source of power loss in this motor is radiation from the ionizer. From knowledge of the emissivity of tungsten, it is possible to convert the graph top left into the graph just below it, which involves the power-loss factor, R_B (radiated power/beam power). The desired operating current density is given by $j = 3.0/(R_B\Phi_0)^{1.4}$, where j is in ma/cm^2 and Φ_0 in kv. All possible operation is not defined by this equation; but if j, R_B, and Φ_0 do not satisfy this relationship, it is possible to find another operating point for which R_A or R_B are reduced without any sacrifice in the value of any other parameter.

Current-Density Effects

The implications of the lower graph at left are worth noting. At an exhaust velocity of 2×10^7 cm/sec ($\Phi_o = 27.5$ kv), a power efficiency of 98 per cent is obtainable with a current density of 7 ma/cm^2, a value which appears easily achievable. At $v = 4 \times 10^6$ cm/sec ($\Phi_o = 1.1$ kv), the same current density implies $R_B = 0.5$, yielding an efficiency of only 67 per cent; and to get an R_B as small as 0.1 requires a current density of 70 ma/cm^2. Currents of this magnitude require such small electrode spacing and electrode apertures that the feasibility of such operation is very doubtful.

The electrode system for an ion motor must accelerate the ions produced to the correct velocity with very little interception of the ion beam and must eject this beam with only a small angular spread. For practical cesium-ion motors, total currents will range from perhaps 4 amp to currents many times this value. Such currents cannot be obtained from a single circular aperture. The practical upper limit to cesium ion perveances (current/potential$^{3/2}$) for a circular aperture is approximately 10^{-8} amp/volt$^{3/2}$. This corresponds, for example, to an ion current of 28 ma at 20,000 volts.

Clearly, the accelerating system must be a large array of apertures or long slits. The latter arrangement has the advantage in compactness and low radiation losses and in ensuring minimum delivery of cesium to surfaces not intended as ionization surfaces. The long slit system has accordingly been chosen as the basis of the design of the electrode configuration.

The use of an accelerate-decelerate

system, as shown in the schematic on page 35, rather than a single acceleration to the final velocity, is required by the necessity of preventing electrons, introduced into the beam for neutralization, from bombarding the ionizer with subsequent overheating and power wastage. In addition, it offers the advantage of permitting larger current densities or, alternately, a larger slit width and accelerating gap.

To obtain a relationship between current, voltage, and slit width, it is necessary to make an assumption about the magnitude of perveances obtainable for each length of slit equal to the slit width. For this application a value of 10^{-9} amp/volt$^{3/2}$ appears reasonable, and leads to a current density of $j = 0.0316\ \Phi_a{}^{3/2}/s^2$, where j is in ma/cm^2, s is in cm, and $\Phi_a \equiv \Phi_0 + \Phi_1$ is the total accelerating potential in kilovolts. If $\Phi_a \gg \Phi_0$ the potential drop along the center of the beam may be much less than Φ_a and the available current density much less than indicated by this expression. In that case, it is also possible to encounter conditions where the limitation occurs not in the accelerating gap but in the decelerating gap, changing completely the basis of this last equation.

This equation can be combined with the lower graph on page 92 or the previously cited equation for j to give the graph at right, or an expression for slit width, as follows: $s = (1.1)(10^{-4})\ (\Phi_a/s)^3(R_B\Phi_0)^{2.8}$.

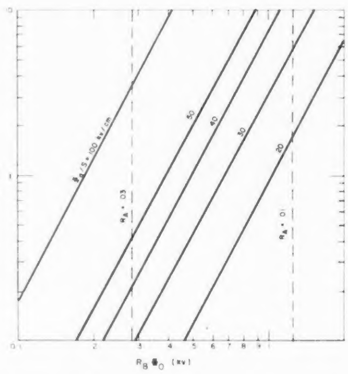
In deriving this expression, it has been assumed that the slit width and accelerating gap are the same, a situation that must approximately obtain for high perveance. The parameter, Φ_a/s, is used because the field strength in the accelerating gap provides a limit to the value of Φ_a. Laboratory tests indicate that values of Φ_a/s up to 50 kv/cm are feasible. Spaceflight conditions are so much more favorable that higher values may be permissible.

Operating Parameters

With this information, it is possible to determine sets of operating parameters for ion motors, such as those given in the table. However, certain areas of ion-motor design have not yet been covered, and a discussion of the table will be deferred until these points are considered.

If the net current leaving the ship is not precisely neutral, the ship must charge up until no further ions can leave. The expulsion of positive ions must be accompanied by a simultaneous ejection of electrons or negative ions. The use of negative ions involves difficulties greater than for the positive-ion generation and acceleration, and electrons provide the most convenient solution. They can be generated in copious quantities with little power and, if accelerated through a potential drop small compared to Φ_0, carry off negligible amounts of power.

The schematic on page 35 shows the source of electrons as a portion of the exit electrode. Electrons are drawn into the beam by the ion space charge fields. It is not clear that complete neutrality of the exhaust can be obtained in this manner; but, at the least, it should be possible to move the turnaround point for ions far enough away from the exit plane that neutralization can easily be completed with an electron gun located peripherally with respect to the rest of the motor.



Slit width (assumed equal to the accelerating gap) as a function of $R_B\Phi_0$ for various values of the average potential gradient in the region between the ionizer and accelerating electrode.

Heating power required to raise a good thermionic emitter to an adequate temperature is very small compared to beam power. Indeed, it is anticipated that, in a compact geometry, the temperature achieved by the exit electrode in the radiation field of the ionizer will be high enough to produce the required electron emission. The potential difference between the emitter and the beam will represent a power loss, but this need be only of the order of 20 volts, which is only 2 per cent of the smallest value of Φ_0 considered here for ion motors.

The emitted electrons will bounce back and forth between the free end of the beam and the ion motor, establishing an electron temperature much higher than the approximately 1500-K ion temperature. Eventually collisions will cause equilibrium between the electrons and ions; but this will be extremely far downstream, and recombinations between the ions and electrons to form neutral cesium are so unlikely as to be completely negligible. There may occur plasma oscillations, which may communicate back into the accelerating region; but at the ion densities of concern here, it is hoped that these can be avoided.

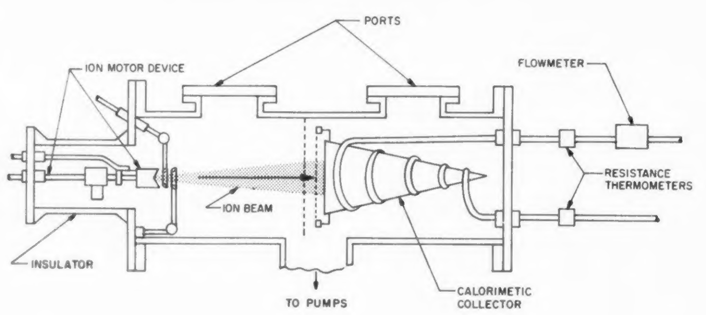
Sputtering and Erosion

Ions intercepted by the accelerating electrode cause a power loss, but a more serious concern lies in the erosion produced by high-energy ions. From information on various ions and target materials, it is estimated that for each ion that strikes the acceleration electrode approximately 12 atoms will be sputtered if the ion energy is 20 kv, and perhaps half as many at 5 kv. For very long missions and low total erosion of the accelerating electrode, this implies that a fraction of the ion beam no higher than one ion in 10^4 may strike the accelerating electrode. This may be feasible for the type of ion source used here, in that the ions are formed at a well-defined surface with only thermal energy. However, scattering of ions by neutrals in the gap may make this achievement impossible. It is necessary to obtain better information than now available on the elastic scattering and charge exchange reactions between cesium ions and atoms before definite conclusions can be drawn. If necessary, it is possible to make accelerating electrodes which are replaceable or have renewable surfaces, but it would be well to avoid such mechanical complications.

At this stage of development, weight estimates are necessarily very rough. If the ionizer is composed of a $^1/_{16}$-in.-thick sheet of tungsten, the back of the box of $^1/_{16}$-in.-thick molybdenum, the heater equivalent to $^1/_{32}$ in. of tungsten, and the radiation shielding $^1/_{32}$ of an inch of molybdenum—the weight per cm^2 of the ionizer-box assembly is 0.016 lb/cm^2. Suppose that the weight of the ion motor, including accelerating electrodes, is twice this, or 0.032 lb/cm^2. The beam power per unit area is $j\Phi_0$. If we assume a total ship weight per unit power low enough to give useful accelerations, we can get a total ship weight per unit ionizer area to compare with the ion-motor weight. To obtain the figures used in the table on page 35, a ship weight of 22.5 lb per kilowatt of beam power has been used. This yields an acceleration of 10^{-4} g at an exhaust velocity of 2×10^7 cm/sec.

It is of interest to take one of the sets of numbers from the table on page 35 and develop it into a motor configuration. For example, consider a motor designed around the parameters in

Schematic of Ion-Motor Test Chamber



column C for a 0.4-lb thrust continuously exerted for a period of 6 months. The total current would be 12.8 amp, and 616 lb of cesium would be required. In the ion-motor arrangement illustrated on page 34, the ionizer and electrode assembly is in the form of a rectangular array 60 cm on a side. For illustration, the slit width and accelerating gap are shown disproportionately large in the figure.

In the design shown, the ionizer is mounted on the reservoir by the delivery-tube structure, and the reservoir is mounted on insulators attached to the bulkhead which separates the ion motor from the portion of the vehicle housing the control and electric power generating equipment. Because of the acceleration of the vehicle, there exists, in effect, a slight gravitational field toward the rear of the vehicle, and this field is utilized in the motor design to hold the cesium in the reservoir. It has been assumed in making this design that the temperature of the hull will be high enough to provide ample cesium vapor pressure. The flow of vapor to the ionizer is controlled by a valve.

Mounting of Electrodes

The accelerating electrode is mounted on insulators so that it can be run at a negative potential. The exit electrode is grounded and is made of an appropriate material to emit copious electrons at its operating temperature.

A hot tungsten-wire diode, held out of the beam, gives a signal proportional to the neutral efflux. This information and the ion current are the basic data which must be fed to a circuit to control the two operating variables—ionizer heater power and cesium valve opening.

The rectangular array shown is a particularly compact design, but numerous others are possible. For example, a configuration with toroidal ionizer surfaces has an advantage in the elimination of end effects; and, for the highest values of exhaust velocity considered here ($v = 2 \times 10^7$ cm/sec), this configuration becomes particularly advantageous in that it can be achieved with a single toroidal aperture of reasonable diameter.

A typical arrangement use in laboratory tests is illustrated above. Grids are used to suppress secondary electrons for dependable collector current measurements. These currents are also verified by measurements of the beam power with the collector shown in the diagram above, and by absolute thrust measurements performed with a suspended collector. The source, including reservoir, valve, and a $^3/_{16}$-in.-diam porous sintered-tungsten ionizer, is operated at a positive potential, Φ_0. The accelerating electrode is run at a negative potential, $-\Phi_1$, and a third electrode is held near ground.

This device has been operated at a current density of 14 ma/cm^2 of ionizer area with a 15-kv net accelerating potential—a beam power of 210 watts/cm^2. The temperature of the ionizer was 1600 K, yielding a calculated radiation of 9.5 watts/cm^2 at an emissivity of 0.25. This temperature is higher than those we have indicated would be required. The reason for this is probably that the ionizer was never raised to a high enough temperature to remove adsorbed oxygen.

In an extended-duration run with this device, the integrated collector current was compared with the consumed cesium. It was observed that 50 per cent of the cesium consumed was delivered as ions to the collector. Estimates based on current drains to the electrodes, and secondary electron emission coefficients derived from the literature, indicated that between 70 and 100 per cent of the cesium was ionized at the tungsten ionizer. The pore sizes and grain sizes were of the order of 4 to 15 microns.

Electrical neutralization of the beam was achieved by operating a thermionic electron emitter around the periphery of the ion beam at the exit aperture of the electrode system. Collector power measurements remained unchanged, indicating an unchanged ion current, while the directly measured current to the collector could be decreased to zero, and even made negative, by increasing the temperature of the electron source. This net flow of electrons is not surprising in a laboratory test. The ions have velocities which are slow compared to the electrons, and at equal currents there is still a net positive space change.

Oscillations have been observed in the ion beam at approximately 100 kc. These were at the correct frequency for ion plasma oscillations, but the variation of frequency with current was approximately as the $^1/_4$ power rather than the expected $^1/_2$ power. The frequency was also correct for a transit time effect, and the oscillations may have resulted from a coupling between the two types of phenomena. These oscillations could easily be quenched by raising the voltage, Φ_1. It is important to determine the cause of these oscillations in order to anticipate behavior in free space.

Efficient Motors

The analysis which has been given indicates that cesium-ion motors producing exhaust velocities in the range 4×10^6 to 2×10^7 cm/sec can be lightweight and efficient. The achievement of derived parameters, such as those given in the table on page 35, may be considered as the goal of an ion-motor development program.

To achieve this goal, several difficulties must be overcome. It is necessary to find an essentially perfect geometry, and it is clear that the mechanical problem of maintaining precise alignment for the extensive testing array illustrated on page 34 is a formidable one. Before making final judgment as to the problem presented by cesium ion-atom encounters in the accelerating gap, it is necessary to have better measurements on scattering parameters and minimum sputtering rates achievable.

Tests on neutralization indicate that the ideas presented in this analysis are sound, but that the testing of neutralization in a laboratory is fraught with

possibilities of error. It does not appear possible to make a laboratory apparatus long enough to achieve thermal equilibrium between the ions and electrons in the exhaust. Questions concerned with growing waves in the exhaust are also difficult to answer completely in a laboratory test, since boundary conditions will be so different in free space.

Nevertheless, tests performed to date do indicate that adequate current densities can be obtained with low-power loss and low-material loss; that neutralization is not difficult to achieve; that oscillations when they occur are easily quenchable; and that structural and insulating materials exist which stand up well in a cesium environment. It appears that the development of cesium-ion motors satisfying requirements for space propulsion is within the domain of present technology.

Suggested Additional Reading

Ion Propulsion

Stuhlinger, E., *J. Astronautics*, 2, 149 (1955); 3, 11 (1956); 3, 33 (1956).

Boden, R. H., *AFOSR-TN* 58–44, Aug. 26, 1957.

Langmuir, D. B., *UCLA Space Technology Course*, Feb. 17–19, 1958, U. of Calif. Engrg. Extension.

Surface Ionization

Taylor, J. B., and Langmuir, I., *Phys. Rev.*, *44*, 423 (1933).

Langmuir, I., and Taylor, J. B., *Phys. Rev.*, *40*, 463 (1932).

Copley, M. J., and Phipps, T. E., *Phys. Rev.*, *48*, 960 (1935).

Datz, S., and Taylor, E. H., *J. of Chem. Phys.*, *25*, 389 (1956).

Shelton, Wuerker, and Sellen, *ARS Preprint*, *882–59*, ARS Meeting, San Diego, Calif., June 8–11, 1959.

Charged-Particle Acceleration

Sources and Collectors for Use in Calutrons, ed. by Wakerling and Guthrie (Office of Technical Services, Dept. of Commerce, Wash. 25, D.C., 1949).

Problems of Physics in the Ion Source, Barnes, MacNeille, and Starr (Office of Technical Service, Dept. of Commerce, Wash. 25, D.C., 1951).

Brewer, G. R., *J. of Applied Physics*, 28, 7 (1957).

Sputtering and Charge Exchange

Electronic and Ionic Impact Phenomena, Massey and Burhop, (Oxford Univ. Press, 1952).

Electron Emission

Venema, Hughes, Coppola, and Levi, *Phillips Tech. Rev.*, *19*, 177 (1957/1958). ◆◆

People in the news

APPOINTMENTS

Alexander H. Flax, vice-president and technical director of Cornell Aeronautical Laboratory, has been appointed AF Chief Scientist for a period of one year, and will serve as scientific adviser to the AF Chief of Staff. **Abraham Hertzberg** has been promoted from assistant department head to head of CAL's Aerodynamic Research Dept., succeeding **Franklin K. Moore,** division director, who will be in charge of the recently regrouped Materials Dept. with the Aerodynamic Research Dept. **Harold A. Cheilek** has been appointed assistant technical director.

President Eisenhower has nominated **Rear Adm. Paul D. Stroop,** chief of Navy BuOrd, to be chief of the newly established Bureau of Naval Weapons. **Rear Adm. William A. Schoech,** former deputy chief and assistant chief, Navy BuAer for R&D, has been designated deputy chief of the new bureau.

Col. Robert W. Paulson has become chief of the Communications Div., AF Directorate of Communications, AF Electronics, Deputy Chief of Staff for Operations.

Albert Wiebe has been appointed Chief of the R&D Branch of the U.S. Small Business Administration.

L. Eugene Root, former vice-president and general manager, Lockheed Missiles and Space Div., has been promoted to the new post of group vice-president, responsible for the Missiles Div. and Electronics and Avionics Div., and the new subsidiary Stavid Engineering, Inc. **William B. Rieke,** former manager of B-70 and JetStar projects, has been upped to assistant general manager of the Georgia Div.

Ernst A. Steinhoff has been appointed director of the newly formed Missile Dept. at Avco Corp.'s Crosley Div. Dr. Steinhoff formerly was deputy technical director in charge of defense products for Aerophysics Development Corp., a subsidiary of Curtiss-Wright. **Evan G. Lapham,** formerly with the National Bureau of Standards, joins the Research and Advanced Development Div. as director of Reference Standards Labs.

Clarence G. Felix, vice-president of Aeronca Mfg. Corp., will be in charge of the new Aerospace Div., while **Peter A. Castruccio,** former director of Westinghouse Astronautics Institute and vice-president of the ARS Maryland Chapter, will be technical director.

John W. Clark will manage the new Hughes Aircraft nuclear electronics lab, while **Joseph H. Beno** will serve as assistant manager; **Stephen S. Friedland,** senior staff physicist; **Thomas D. Hanscome,** manager, radiation effects department; and **Herbert L. Wiser,** manager, new radiation sources department.

Charles C. Botkin, former manager of GE's nuclear ordnance projects operation in the Missile and Space Vehicle Dept., has been named manager of the department's new Missile, Arming, and Fuzing Program Office; **Robert J. Kirby,** former manager of the MSVD aerophysics engineering operation, succeeds Botkin. **William Raithal** becomes manager, engineering, for GE's Special Programs Section. Dr. Raithal formerly served as manager, Advanced Engineering Operation, MSVD.

Alex E. S. Green has been named chief of physics at Convair (San Diego) Div. of General Dynamics. Dr. Green formerly was professor of physics and scientific director of the Tandem Van de Graaff nuclear research program at Florida State Univ.

William M. Webster has been appointed director, Electronic Research Lab, RCA Laboratories.

Albert G. Handschumacher has been elected president of Lear, Inc. He has served on Lear's Board of directors and as a member of its executive committee since 1957.

Roy G. Knutson has been named manager of Advanced Engineering for Autonetics, a Div. of North American Aviation.

Frederick A. Fielder has been elected vice-president and general manager of the Loewy-Hydropress Div. of Baldwin-Lima-Hamilton Corp. Fielder succeeds Erwin Loewy, founder and head of Loewy-Hydropress and vice-president of its parent company, who died last July.

Edward W. Herold has been appointed vice-president for research, Varian Associates, while **Louis Malter** becomes head of the new Vacuum Products Div. Herold formerly was director of RCA Labs' Electronic Research Lab, and Dr. Malter previously was director of central research at Varian.

Herman L. Coplen Jr. has joined ARPA, and will specialize in space research and ballistic missile evaluation. Coplen previously was head of the Systems and Control Dept. at Aerojet-General's Liquid Rocket Plant. Aerojet has designated **Rudi Beichel** as project engineer for the second-stage rocket engine for the Saturn space vehicle.

Thomas W. Layton and **Robert K. Whitford** have been named associate managers of Space Technology Laboratories' Inertial Guidance Dept. and Control and Simulation Dept., respectively.

AF Lt. Col. Kermit E. Beary has been assigned to Republic Aviation as AF plant representative.

Robert L. Ruth has been named chief engineer, Marine and Ordnance

Botkin

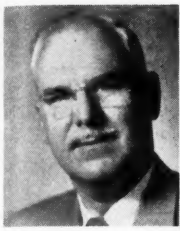
Kirby

Raithal

Fielder

Herold

Malter



Silk

Kimball

Dept., Vickers, Inc. He had been engineering systems manager on systems design projects for supersonic aircraft.

Fred Stolte, formerly with NOTS, has joined McCormick Selph Associates as senior engineer.

Todor Dimoff has joined the Engineering Mechanics Section of the National Bureau of Standards.

E. O. Vetter, a former assistant vice-president, Texas Instruments, has been elected a vice-president. He also has been made division manager of the Metals & Controls Div. **C. J. Thomsen,** vice-president and division manager of the M&C Div., will resume the position of vice-president, Control and Finance.

W. Paul Smith has been appointed a vice-president of American Bosch Arma Corp.

Harry B. Henshel, executive vice-president, Bulova Watch Co., has been elected president of the company, succeeding John H. Ballard, who is retiring. **William A. Mullio** has been named project manager for development of a general purpose mechanical timer for missile fuzing and programing systems at Bulova Research and Development Labs, Inc., a subsidiary.

Loren K. Hutchinson has been promoted from manager, industrial relations, to works manager for Wyman-Gordon's Worcester, Mass., plant.

C. Earnest Silk has been named director of development for solid propellants and explosives operations of the Energy Div., Olin Mathieson Chemical Corp.

Lt. Cmdr. Edmond A. Basquin has been named director of divisional services for the G. T. Schjeldahl Co.

Ronald Compton has been upped from associate engineer, Bendix Computer Div., to senior engineer for computer design at the division's main plant.

C. E. Deardorff has joined Southwestern Industries, Inc., as chief engineer.

Louis A. Pipes, professor of engineering at UCLA, has been appointed a consultant in systems engineering to Gulton Industries, Inc.

T. Walter Ekberg and **William D. Leetch Jr.** have been appointed refractories engineers by Norton Co.

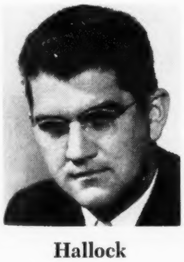
Andrew C. Bayle has been elected vice-president, engineering, of the Waltham Precision Instrument Co.

David T. Kimball has joined Telecomputing Corp. as vice-president and general manager of the Whittaker Gyro Div. **Melvin B. Kline** has been named director of R&D at Brubaker Electronics, a subsidiary, while **Peter L. Bealer** has been promoted from advertising manager to director of advertising and public relations of the parent company.

Robert D. Hallock becomes manager of Leach Corp.'s Inet Div., while **William F. Hurst** becomes director of quality control at the Compton facilities.

Charles L. Davis and **Clyde A. Parton,** general managers of the Aeronautical and Ordnance Divs., respectively, of Minneapolis-Honeywell's Military Products Group, have been named divisional vice-presidents of the group. **Finn J. Larsen** former director of research at M-H, has been named to the new post of vice-president, research. **William F. Newbold** has been appointed director of research for the Brown Instruments Div.

David M. Checkley has been named president of Vitro Engineering Co. He formerly was general manager of the Industrial Engineering Div. of



Hallock

Hurst

Davis

Parton

Arthur G. McKee & Co.

Warren C. Dunn, former general sales manager, Southwestern Industrial Electronics, Inc., has been appointed manager of marketing for Stromberg-Carlson, San Diego.

Jerome I. Davis, former general manager, Aircraft Equipment Div., Consolidated Diesel Electric Corp., has been upped to division vice-president of the division.

George F. Kennard and **Thomas R. Horton** have been promoted to managers of the Research and Engineering Dept. and new Systems Analysis Dept., respectively, at the Federal Systems Div. of International Business Machines Corp.

Knox McIlwain has been appointed special representative for Burroughs Corp.; **Alva R. Perry Jr.** becomes the new plant manager of the Military Electronic Computer Div.

Martin Schilling has been appointed assistant for program planning at Raytheon; **Thomas L. Phillips,** assistant manager, Missile Systems Div.; **Harold Asquith,** NATO Hawk program manager at the division. Appointed managers of the five new subdivisions of the Government Equipment Div. are **Glenn R. Lord,** Airborne Electronic Equipment, Sudbury, Mass.; **Fritz A. Gross,** Heavy Electronic Equipment, Wayland, Mass.; **Gordon Humphrey,** Santa Barbara Subdivision, Calif.; **Roger Hamel,** Submarine Signal, Portsmouth, R.I.; and **Harold M. Mart,** Systems Management, W. Newton, Mass. **W. Crawford Dunlap,** director of semiconductor research, has been named editor-in-chief of *Solid State Electronics,* a new international publication dealing with transistors and other solid-state devices.

Swedlow Inc. has appointed the following managers: **K. G. Granger,** Eastern Contracts Dept.; **C. M. Phinny,** Western Contracts Dept.; **R. H. Fisher,** sales manager for commercial products; and **Carey Carpenter,** Technical Service Dept.

John J. Dempsey, manager, Servomechanisms, Inc.'s Mechatrol Div., and **William T. Smither,** general manager, Los Angeles Div., have been appointed vice-presidents of SMI.

Harold A. Wheeler has been elected a vice-president and director of Hazeltine Corp.

Wm. Merton Nellis and **Wyman M. Anderson** have joined American Electronics Co. as senior design and development engineer and quality manager and military contracts administrator, respectively.

William B. Bergen, formerly executive vice-president of Martin Co., has been elected president. **George H. Kunstadt,** former engineering projects manager, Airborne Systems Dept., RCA's Defense Electronic Products Div., has been made technical director, Ground Support Equipment Dept., Martin's Baltimore Div.

Robert Geiger becomes project development manager, Twin Coach Co. He formerly was director of engineering planning and tooling.

William E. Nolan has been elected vice-president and general manager of Rolle Mfg.

Walter C. Williams, former chief of NASA's High-Speed Flight Station at Edwards AFB, Calif., has been named an associate director of Project Mercury, with offices at Langley Research Center, Va. **Paul F. Bikle,** former technical director, AF Flight Test Center, Edwards, succeeds Williams.

Allen Breed has been elected president of the newly formed R.E.D.M. (research, engineering, development, manufacture) Corp. Other officers are **Seth Harrison,** chief executive officer, and **Fred Kahn,** former civilian chief of the Bomb, Rockets, Warheads, and Pyrotechnic Branch, Army Ordnance Ammunition Command, as board chairman.

HONORS

Gwilym A. Price, board chairman of Westinghouse Electric Corp., will be awarded the ASME John Fritz Medal, an annual award made for notable scientific or industrial achievement, at the ASME meeting in December.

Raymond Letner, project engineer, Melpar, Inc., has been awarded the National Bureau of Standards Certificate of Award for the development of a unique welding method.

David M. Potter, president of Potter Aeronautical Corp. and Potter Pacific, and designer of the Pottermeter, an instrument used to determine amount of liquid flowing from such things as the fuel tank of a jet or from bulk storage tanks, will receive an Edward Longstreth Medal from The Franklin Institute, Philadelphia.

Morton B. Prince and **Martin Wolf** of Hoffman Electronics' Semiconductor Div. will receive the Marconi Premium award presented by the British Institution of Radio Engineers for their award-winning paper, "New Developments in Silicon Photo-Voltaic Devices."

Solid-Core Nuclear Rocket

(CONTINUED FROM PAGE 27)

is met. It is usually expressed in kilowatts or megawatts of heat energy per pound of combined reactor core, reflector, and pressure shell. Since the total weight is the important quantity, obtaining a high-power density in a small core that is surrounded by a massive reflector and pressure shell is no particular virtue. Reactor designs must be compared on a total power-total weight basis.

In some cases, neutronic considerations place a limit on power density, while in other cases structural and heat-transfer considerations limit power density. A design is usually iterated until all three considerations are more or less equally limiting, to arrive at the highest power density possible for that system.

For uniform uranium loading, the fission (power) distribution is proportional to the thermal neutron flux distribution. The curves on page 27 show typical distributions with an unreflected reactor and with a neutron reflector surrounding the core. The maximum-to-minimum variation is much less in the reflected case than in the unreflected. Thus, the core power density is more uniform in the reflected case. Which of the two has the greater over-all power density, however, can be determined from detailed calculation, since reflector weight must be included in the reflected case.

The primary problems involving the structural design are support of the core within the pressure shell against the pressure drop across the core; thermal stresses in fuel elements and structural elements; and the necessary dimensional clearances to avoid interference of adjacent components resulting from differential thermal expansion.

The approximate core pressure drop may be calculated from the relation

$$\Delta P = C_2 \frac{G^2 T_m}{P_{ave} m}\left(\ln \frac{\rho_1}{\rho_2} + \frac{2fL}{D}\right)$$

where C_2 is a dimensional constant, G is the mass flow rate per unit cross-sectional area, T_m is the mean bulk gas temperature for the process, P_{ave} is the arithmetic average pressure for the process, m is the propellant molecular weight, ρ_1 and ρ_2 are the inlet and exit propellant densities, f is the mean friction coefficient for the process, L is the core length, and D is the flow passage hydraulic diameter.

Devising an adequate method of supporting the core within the pressure shell requires ingenuity in mechanical design, as well as a thorough knowledge of the physical properties as a function of temperature of all the materials involved. In addition to the loads on the core support resulting from the propellant pressure drop, provision must also be made for the axial and lateral acceleration forces anticipated for the intended flight application for the reactor. In general, the acceleration forces are small compared with the pressure drop forces.

The elastic thermal stresses in the fuel elements may be calculated from the approximate relation

$$\sigma_{th} = \frac{E\alpha}{1 - \nu}(T_{max} - T_s)\beta$$

where E is Young's Modulus for the material, α is the thermal coefficient of expansion, ν is Poisson's ratio, T_{max} is the maximum internal fuel-element temperature, T_s is the surface temperature, and β is a geometric factor less than unity. The temperature difference in this equation is proportional to the local power density.

While it is not possible to ignore internal thermal stresses either within the fuel elements or structural elements, the preceding equation cannot be taken literally except for brittle materials. For ductile materials, or materials in the plastic range, thermal stresses are greatly reduced, and thermal stress limits are best obtained by experiments in which the design operating condition is simulated as closely as possible.

Heat-transfer coefficients are calculated from the familiar turbulent flow relation

$$\frac{HD}{K} = C_4\left(\frac{\rho V D}{\mu}\right)^{0.8}\left(\frac{\mu c_p}{K}\right)^{0.3}$$

where C_4 is a constant for a given passage length-to-diameter ratio, H is the heat-transfer coefficient, D is the passage hydraulic diameter, K is the propellant thermal conductivity, ρ is the propellant density, V is the bulk velocity, μ is the propellant viscosity, and c_p is the propellant specific heat. All fluid properties are evaluated at the arithmetic average of the bulk and surface temperatures.

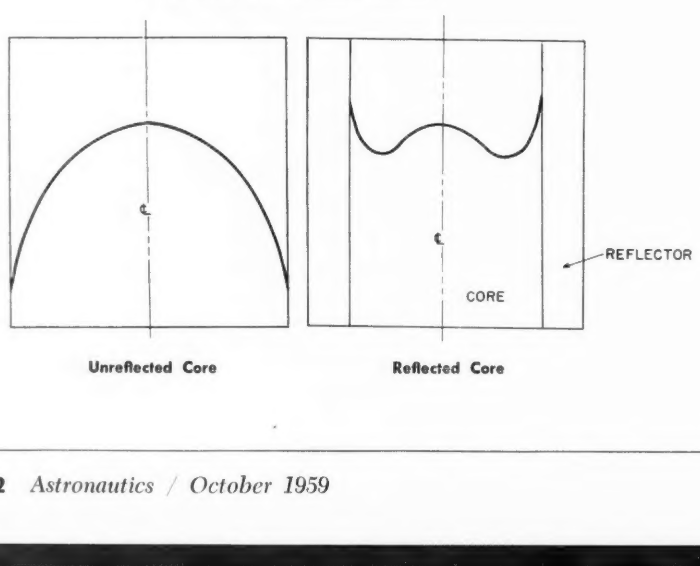
Since the heat-transfer coefficient for a given passage and flow rate is roughly constant, the wall-to-gas temperature difference will vary axially in the same manner as the axial power distribution. Further, the mean wall-to-gas temperature difference for a given fixed reactor geometry and power distribution is given approximately by the relation

$$\Delta T_m = C_5\,(T_{exit} - T_{inlet})$$

where C_5 is approximately constant over a wide range of Reynolds' numbers, T_{exit} is the reactor exit propellant temperature, and T_{inlet} is the reactor inlet propellant temperature. The graph on page 27 shows typical axial power and temperature profiles.

A further practical consideration having to do with over-all pressure drop and flow balancing among the many parallel passages of the reactor core heat exchanger is a Mach number, or compressibility, limitation. The graph on page 27 shows a typical pressure variation with increasing Mach number in the direction of flow for a constant area passage with heat addition. As shown in this graph, the absolute pressure in the flow passage decreases by over 60 per cent in going from a Mach number of 0.4 to a Mach number of unity. This greatly

Neutron Flux Distributions



Unreflected Core **Reflected Core**

increases the structural load on the core. The increased sensitivity of pressure drop to change in Mach number at the higher exit Mach numbers also causes additional difficulties in flow balancing when engineering tolerances and attainable power distributions are considered.

In theory, it is possible to operate a reactor with all flow passages having a sonic exit condition. Such a reactor would have minimum frontal area and maximum pressure drop for a given length and propellant exit temperature. Since pressure drop varies as shown by the equation on page 27, a small reduction in mass flow rate per unit area (power density) will greatly reduce pressure drop. Therefore, an exit Mach number of 0.5 or less is a desirable design value.

One of the most important aspects of a nuclear-rocket propulsion reactor is that of combined neutronic and flow control. It is necessary to control the reactor to maintain a stable design steady-state condition, as well as to bring the reactor up to design conditions of flow rate and temperature in an extremely short time, compared with better known power reactors.

The two most important characteristic response times, or so-called time constants, associated with power and flow transients in a reactor, are the thermal heat capacity time constant and the neutronic power time constant. The first relates to the rate at which reactor temperature will rise with internal power generation and propellant flow, and the second relates to the rate at which power can increase resulting from increasing the neutron flux. If the reactor has a negative temperature coefficient of reactivity (neutron multiplication decreasing with increasing temperature), then the neutronic time constant provided by the neutron control should be of the same order as the thermal time constant. Further, the flow control response time need not be appreciably faster than the thermal time constant.

The thermal time constant is defined approximately as follows:

$$T_c = \frac{(W\,C_p)_{core}}{(\dot{W}\,C_p)_{propellant}}$$

where W is the mass of the active core, $\dot{W}$ is the propellant mass flow rate, and C_p in the numerator and denominator is the specific heat of core and propellant, respectively. This time constant represents the time required to produce 63 per cent $(1 - 1/e)$ of the steady-state temperature change associated with a step change in power, or flow rate.

The neutronic time constant is called the reactor period and is defined by the relation

$$T_n = \frac{l^*}{\delta K_{eff}}$$

where l^* is the mean effective lifetime of a neutron and δK_{eff} is the effective excess neutron multiplication factor. The multiplication factor is defined as the ratio of the number of neutrons in any one generation of the corresponding number of neutrons of the preceding generation. The amount this multiplication factor differs from unity is called the excess multiplication factor. The physical significance of the reactor period is that in this time, the reactor power increases by a factor e (2.72).

A negative temperature coefficient of reactivity is extremely desirable from the standpoint of reactor neutronic control, since it automatically limits the maximum reactor temperature for any control rod setting. Three primary phenomena contribute to a reactor's negative temperature

coefficient. These are:

1. Thermal expansion of the core.
2. Decrease in propellant density with temperature.
3. Decrease in thermal neutron fission cross-section with increasing neutron temperature.

Item 1 is to some extent within the control of the designer, in that the specific core design will determine its gross expansion with increasing temperature.

Item 2 results from the neutron moderating ability of hydrogen, which is directly proportional to the local hydrogen density. The higher the core temperature, the less dense the hydrogen, and the lower the slowing-down cross-section.

Item 3 depends on the neutron energy spectrum causing fissions. The more thermal (well moderated) the reactor, the greater the decrease in reactivity caused by temperature increase in the moderator and reflector.

In general, even with an inherently stable negative temperature coefficient, it is possible to have neutron control or flow control transients in which reactivity can be added at a rate faster than the reactor can deliver energy to the propellant. If these rates are too greatly out of balance—that is, if a severe neutronic power excursion occurs, with an instantaneous power many times that which the reactor was designed for—destruction of the core resulting from thermal expansion waves, or from vaporization, will occur.

The most common type of reactor neutronic control is by means of removable rods having high thermal neutron absorption cross-sections. Common materials for such rods are boron and cadmium. The actuating mechanism for the control rods must have the necessary time response characteristics. Other requirements in the design of the neutronic control are adequate cooling of both the actuators and control rods themselves, which are internal to the core.

The core design problems associated with fast startup have to do with thermal expansion and thermal shock. As an example, the fuel elements will heat more rapidly than other parts of the reactor during a rapid startup. Consequently, sufficient physical clearance must be provided between the elements and structure to prevent mechanical interference when extreme temperature differences exist. The thermal shock characteristics of the fuel elements and structure must also be taken into account when establishing a minimum startup time.

Nonnuclear Components

The design of the nonnuclear components, such as the reactor pressure shell, propellant nozzle, and the previously mentioned control actuators, present more-or-less straightforward problems in mechanical design. They differ from similar components in chemical-rocket systems in that heat from gamma and neutron absorption is generated within the components. This internal heating must be added to the thermal conduction, convection, and, in some cases, thermal radiation, that would otherwise be present under the same temperature and flow conditions. In general, the magnitude of the gamma and neutron heating does not affect nozzle design significantly, although it makes an appreciable contribution to the cooling requirements of the pressure shell and control actuators.

The phenomenon of radiation-induced deterioration of physical properties of materials has been the subject of experimental research for many years. A great deal has been learned about the effects of integrated exposure to both gamma and neutron radiation of many materials. These results are largely available in several unclassified reactor materials handbooks.

The total integrated exposure to radiation fields is roughly the same for nuclear propulsion reactor materials as those of many other reactors which operate at lower neutron flux levels but for much longer periods of time. The rates at which total exposures are applied, however, are much higher in the case of rocket-propulsion reactors. In the absence of information on rate effects, the same general criteria are used in the selection of rocket-propulsion reactor materials as for other nuclear reactors.

In addition to the reactor materials themselves, consideration must be given to components outside the reactor, such as control rod actuators, seals, and bearings. Whether suitable radiation resistant materials can be chosen or local shielding provided depends on the specific design under consideration.

Suggested Additional Reading

Bussard and DeLauer, *Nuclear Rocket Propulsion,* McGraw-Hill, 1958.

Glasstone, S., *Principles of Nuclear Reactor Engineering,* Van Nostrand, 1955.

The Reactor Handbook, AECD-3646, U.S. Atomic Energy Commission.

McAdams, W. H., *Heat Transmission,* 3rd Ed., McGraw-Hill, 1954.

Roark, R. J., *Formulas for Stress and Strain,* 3rd Ed., McGraw-Hill, 1954.

Dienes and Vineyard, Radiation Effects in Solids, *Interscience,* 1957.

Taylor and Kirchgessner, *Measurements of Heat Transfer and Friction Coefficients for Helium Flowing in a Tube at Surface Temperatures up to 5900 R.* Presented at ARS Summer Meeting, San Diego, June 8–11, 1959.

Durham, F. P., *Pressure-Temperature Relation for Constant-Area Compressible Flow of a Gas, Considering Heat Transfer and Friction with Constant Wall Temperatures,* LA-2129, Los Alamos Scientific Laboratory, July 1957.

Schultz, M. A., *Control of Nuclear Reactors and Powerplants,* McGraw-Hill, 1955. ◆◆

Nike-Ajax Grain

Olin Mathieson's Ordill plant made this experimental internal-burning solid-propellant grain for the Nike-Ajax missile. The Army has awarded Olin Mathieson a contract for study of propellant for Nike-Zeus.

Canned Liquid-Rocket Engines

(CONTINUED FROM PAGE 39)

A large number of storable fuels and oxidizers have been investigated for use in rocket motors. The top table on page 38 lists some of the best-behaved of the proved storable hypergolic systems. These combinations give smooth combustion over a wide range of combustion-chamber pressures. The ability to start and stop motors using these propellants is another of their big advantages. It is important to note that some liquid propellants stored in sealed tanks have proved to have better storage characteristics than do the best available solid propellants. For instance, the UDMH-IRFNA system has been stored successfully for 3 yr at 165 F.

Moreover, there are currently several other very promising storable, high-energy hypergolic propellant combinations under investigation. These are summarized in the bottom table on page 38. One of the more promising is stabilized hydrazine and tetrafluoro-hydrazine. Calculations give a sea-level specific impulse of 275 sec at a chamber pressure of 300 psi for this combination.

The canned liquid-propellant system is flexible in part because a variety of propellants can be used in it. The combination of nitrogen tetroxide and lithium borohydride is an unusual example. Both materials are potentially available in commercial quantities at low cost. Preliminary estimates indicate that specific impulses of 290 to 300 sec should be attainable with this combination at sea-level conditions. Even though the lithium borohydride is not a liquid, it could be used in a slurry with a liquid. Another noteworthy combination is IRFNA and lithium. It is calculated that these propellants will attain high-altitude specific impulses in excess of 300 sec. Lithium is a solid at ordinary temperatures and requires heating to the relatively low temperature of 356 F to operate in a liquid engine.

In systems where volume limitations are a major design factor, the density of propellants is quite important, even at the expense of some loss in impulse. A very promising propellant combination in this category is aluminum borohydride and bromine pentafluoride, which yields a density specific impulse of 450 sec. This significantly exceeds the current state of the art for even the best of the solid propellant formulations.

Using the hypergolic characteristics of present storable liquid propellants, experiments have already proved full-range variable-thrust engines. IRFNA

and UDMH have been particularly successful in variable-thrust engines. These engines promise to be of major value for missiles requiring thrust programing, and for space vehicles requiring precise on-off and thrust-level control. The diagram on page 39 shows the NOTS variable-thrust research motor. The ease of changing the thrust level of this motor and starting and stopping it is readily apparent from the hand throttle.

The demonstrated characteristics of the storable systems make them highly attractive for several weapon applications. Among these are air-to-air missiles of sufficient size to warrant the use of the canned liquid system, and where thrust programing is required to sustain the missile at a high Mach number not exceeding the structural limits of the missile under aerodynamic heating. Because the demonstrated short-time, high-temperature characteristics of the liquid propellants are substantially better than those demonstrated to date by the solid-propellant systems, the liquids appear to be the best available for use in missiles carried aboard supersonic aircraft. For large ground-launched missiles, the canned liquid-propellant systems appear to be much more suitable than do either solid or cryogenic systems because of instant readiness, coupled with high performance. And, once again, the canned-propellant rocket needs little in the way of ground support. Because of these factors, the application of storable liquids to the IRBM and the ICBM is particularly appropriate.

Canned, storable liquid-propellant motors are also attractive for use in the upper stages of space vehicles when precise thrust vectoring and thrust cutoff are required to accomplish the mission. Where it is desired to launch satellites into circular orbits, the propulsion can be programed to obtain 99 per cent of the velocity vector and then the final-stage liquid engine turned off. Ground stations can then compute the amount of impulse required to complete the desired circular orbit and turn on the system for a controlled period.

At the moment, NOTS is testing motors with thrust range of only a few ounces and up to 10 lb. These micromotors give high promise for controlling the spatial orientation of satellite and missile systems.

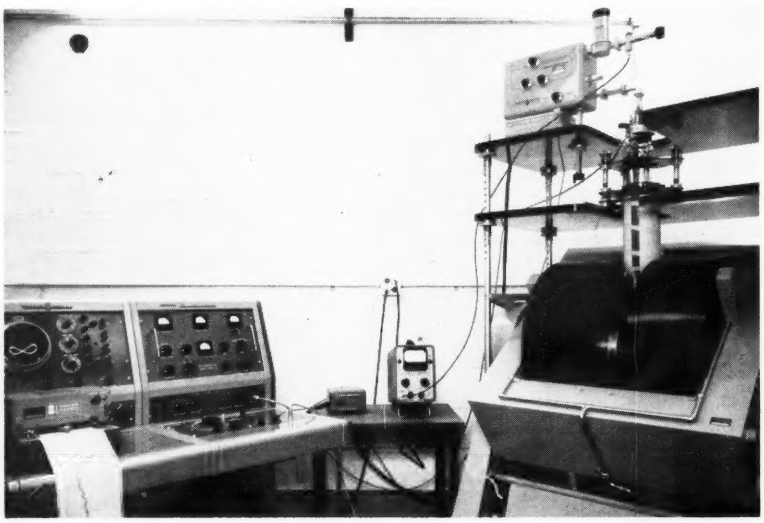
Finally, canned liquid-propellant rocket systems are better able to withstand space environments than even solid-propellant motors. Moreover, the characteristics of liquid propellants will be required for final-stage motors of vehicles en route to Venus or to the moon. There, they can be fired to achieve the precise orbit about the celestial body, or even to accomplish a soft landing of the payload. The photo on page 39 shows a model of a lunar-probe landing vehicle with a storable liquid-propellant rocket system now under study. ◆◆

Free-Radical Fuels

(CONTINUED FROM PAGE 44)

On the other hand, the prospect of an impulse near 500 sec at 15 mole per cent H-atoms in H_2 has a very definite appeal. The big problem lies in the production of material containing even this high a concentration of atoms, since there are probably barely enough molecules in the system to prevent some direct contact between atoms, even in the most favorable geometry. There is presumably no significant barrier to prevent recombination of atoms which are nearest neighbors, although this assumption may not be valid at sufficiently low temperatures. If atoms could be stabilized in direct contact with each other, then one might hope to achieve impulses of 1000 sec or greater at atom concentrations above 50 per cent.

Solids containing low concentrations of stabilized free radicals can be produced readily, either by low-temperature trapping of gaseous radicals or by irradiation of materials at low temperature. The basic problems in producing concentrations in excess of about 1 mole per cent in the solid involve heat dissipation. When radicals are trapped from a gas discharge, for example, the heat of sublimation as well as the kinetic energy of the radicals must be dissipated on the collecting surface. As a layer of radical-enriched solid, which is generally a poor heat conductor, builds up, it becomes increasingly likely that the heat released by further condensation of radicals and inert molecules will cause recombination of already trapped atoms. Extremely slow deposition from the gas phase or precooling of the gas molecules before trapping show some promise in reducing the heating effects.



Studies of low-temperature free-radical reaction rates under an AFOSR contract at Aerojet-General center around this Varian electron-paramagnetic resonance spectrometer. The unpaired electrons in the free radicals absorb microwave energy when placed in a strong magnetic field; the nature of the absorption spectrum obtained with changing field strength gives clues about the interactions between the trapped radicals and the stabilizing matrix. The rate of disappearance of radicals is measured by observing the decrease in spectral intensity with time while the sample is held at constant temperature. This equipment permits measurements at temperatures as low as 2 K, using pumped liquid helium.

The irradiation of cold solids is subject to a similar difficulty, in that hot spots are produced in the solid during irradiation (e.g., with gamma rays). As the radical concentration builds up, it becomes increasingly likely that a hot spot will occur near enough to

some trapped atoms to cause recombination. In fact, gamma-irradiation of solids at either liquid-helium or liquid-nitrogen temperature generally has produced ultimate radical concentration plateaus at about 0.01 molar or less.

One unusual technique which has been suggested for the prevention of atom recombination in the solid is magnetic alignment of all the electron spins in the system, thus preventing pairing of the electrons to form bonds. Calculations show, however, that fields in the megagauss range (presently unattainable) would be required, even at temperatures near 1 K.

To date, the most promising means for stabilization of light free radicals involves the use of very low temperatures to prevent migration and subsequent recombination. The alternative of stabilization by adsorption on surfaces or by complexing with other species has the double disadvantage that the weight of material per radical is increased and the available energy is reduced by the heat of adsorption or complexing. If an appreciable fraction of the energy available from atoms is to be realized, it is essential that the stabilization not involve any chemical bonds of more than a few kilocalories in energy.

Activation Energies

Under an Air Force Office of Scientific Research contract at Aerojet-General, we have measured activation energies in the range of 4–7 kcal/mole for the recombination of hydrogen atoms and other free radicals trapped in solids at temperatures slightly above that of liquid nitrogen. This "stabilization energy" represents a loss of only a few per cent of the recombination energy of hydrogen atoms. It is assumed that the stabilization is due to caging in holes in the lattice; the low temperature is necessary to prevent diffusion out of the cage. The observed stabilization of H in solid hydrogen irradiated at 4.2 K may actually involve, in addition, a lowering of the vapor pressure of the H, since it is doubtful that very strong cages will be formed in the very weakly bonded H_2 matrix, which melts at only 14 K.

The lowest practical temperature for storage of frozen radicals in quantity is the boiling point of natural helium (4.2 K). Continuous refrigeration to lower temperatures has been achieved, but requires, at present, quite complex and massive equipment for relatively small samples. Since 4.2 K is a sufficiently low temperature to maintain H_2 as a solid and to stabilize at least low concentrations of hydrogen atoms, present information indicates that the H-H_2 fuel will probably have to be surrounded by a liquid-helium-filled jacket continuously during storage.

The principal uncertainty in the combustion properties of a free-radical fuel also affects the storability of the material. As pointed out, the energy required to free a stabilized atom must be small with respect to the recombination energy, or the energetic advantage of the radicals is lost. This requirement, however, carries with it the consequence that the heat evolved by recombination of one radical pair would be sufficient to promote recombination of many stabilized pairs surrounding the initial site. This may not be too serious a problem if a sufficiently large fraction of the recombination energy is carried away as kinetic energy of the escaping, newly formed molecule. However, heat capacities are extremely low near liquid helium temperature, and a small fraction of the evolved energy would serve to heat the lattice enough to promote additional recombinations. Whether the resulting chain process would lead to detonation or could be controlled to give smooth combustion has been the subject of some preliminary calculations, but the answer will probably have to come from experiment, once fairly high concentrations of stabilized radicals have been attained.

The over-all free-radical picture may seem rather bleak at this stage, from an application standpoint, but then so did the re-entry problem only a short time ago. It can still be hoped that continuing basic research on these most unusual systems may produce the necessary breakthrough, and that first bucketful of propellant atoms. ◆◆

NSF Offers Funds for Graduate Laboratories

The National Science Foundation, in a new program, will support graduate-level laboratories for engineering and natural sciences in institutions of higher education by paying up to 50 per cent of the cost of renovations or additions of standard fixed equipment. Persons or institutions should submit proposals for this aid to the appropriate division of NSF by Dec. 1, 1959—for the physical sciences, to the Division of Mathematical, Physical, and Engineering Sciences; for the natural sciences, to the Division of Biological and Medical Sciences—both at the Washington, D.C., headquarters. Grants under this program will be made about June 1, 1960.

Government contract awards

Avco Gets $36.6 Million Job for Minuteman Nose Cone R&D

The AF has awarded a $36,655,000 prime contract to Avco's Research and Advanced Development Div. which calls for prototype development of the re-entry nose cone for the Minuteman solid-fuel ICBM.

CAL to Design, Build New AF Hypersonic Wind Tunnel

Cornell Aeronautical Laboratory will design, build, and operate the world's first wind tunnel for long-duration testing of hypersonic missiles and space vehicles under actual atmospheric flight conditions under a $3.1 million contract with ARDC.

Chrysler to Build Redstone-Type Boosters for Project Mercury

Chrysler Corp. has a contract from ABMA to build eight Redstone-type missile boosters for Project Mercury. Present plans call for employing the boosters with manned trainer capsules. In addition, Chrysler has been selected to perform certain developmental engineering studies on the analysis and design of airborne instrumentation for the Mercury program.

Miniature Mass Spectrometers

Consolidated Systems Corp. has received a $98,600 contract from NASA's Goddard Space Flight Center for development of miniature mass spectrometers that will be placed in orbit to measure and analyze the elements of the exosphere.

High-Level Radiation Lab

Vitro Engineering Co. will design and engineer a $1.7 million high-level radiation laboratory for the Naval Research Lab, in support of the Navy's nuclear development program.

Advanced Radar Equipment

General Electric Heavy Military Electronics Dept. has been awarded a $22-million contract from AMC's Rome Air Material Center for production of Radar Course Directing Groups which will automatically detect and track air targets so that the air situation can be rapidly managed.

Project Mercury Guidance

A contract to manufacture LEV-3 gyro components to control modified Redstone rockets for launching the Mercury test capsules has been awarded to Waste King Corp. by ABMA.

Page Gets $10 Million Contract For Communications Link

Page Communications Engineers, Inc., has received a $10 million AF contract to design and build a multichannel, tropospheric-scatter, telephone, teletype, and data communications network linking the United Kingdom, Spain, and Morocco.

AF Awards Ryan Study Contract For New VTOL Vertifan Concept

The Air Force has awarded Ryan Aeronautical a preliminary aircraft design study contract for its Vertifan system, a new fan concept of combining vertical takeoff and landing characteristics with high-speed forward flight.

Environmental Test Chambers

Army Ordnance Research Lab, Picatinny Arsenal, has awarded International Radiant Corp. a contract for environmental test chambers with altitude simulation to 200,000 ft, upper temperature range of 400 F, and a full humidity range.

SYNOPSIS OF AWARDS

The following synopsis of government contract awards lists formally advertised and negotiated unclassified contracts in excess of $25,000 for each Air Force, Army, Navy, NASA, and ARPA contracting office:

AIR FORCE

AF CAMBRIDGE RESEARCH, LAURENCE G. HANSCOM, FIELD, BEDFORD, MASS.

Study of disturbances in radio reception associated with passage of orbital bodies, $78,868, **General Electric**, French Rd., Utica, N.Y.

Telemetering transmitters, $30,075, **Telechrome Mfg. Corp.**, 28 Ranick Dr., Amityville, N.Y.

Develop dual channel high frequency radio transmitter and transistorized analog-to-digital binary coding telemetering device, $70,771, **Dynatronics, Inc.**, 717 W. Amelia Ave., Orlando, Fla.

Design and develop a prototype airborne gravity meter, $195,863, **Gravity Research Corp.**, 6606 Lamar Blvd., Austin, Tex.

NASA CONTRACTS FOR JUNE

Contractor	Obligation	Program
Aerojet-General	$ 140,000	Fabrication, static-firing, and shipping booster stage of Scout rocket.
AFBMD	$7,500,000	Initial funding for 8 modified Atlas boosters to be used in the three-stage Vega rocket.
AFBMD	$5,870,000	Initial funding for 11 Thor boosters to be used in the three-stage Delta rocket.
AFCRC	$ 50,000	Test of drogue chutes for Project Mercury.
ARDE-Portland, Inc.	$ 90,000	Investigation of performance of refractory materials on rocket nozzle liners.
AOMC	$ 150,000	Partial funding for 12 Honest John's and 24 Nike's for sounding-rocket program.
AOMC	$ 150,000	Studies of problems of soft lunar landings.
CalTech	$ 130,000	Construction of lunar seismograph.
Columbia	$ 130,000	Construction of lunar seismograph.
General Electric	$ 390,000	Study of plug-nozzle engine.
Grand Central Rocket Co.	$ 180,000	Demonstrate feasibility of a unique design for solid-propellant rocket engines.
Hughes Aircraft	$ 200,000	Design and construction of atomic clock using ammonia vapor.
MIT	$ 100,000	Design and build prototype instrument to measure density of plasma between earth and moon.
Motorola	$ 60,000	Command receivers for Scout guidance and telemetry systems.
NRL	$ 80,000	Lunar data acquisition and recording system.
NRL	$ 100,000	Preliminary design work on advanced detectors to measure ultraviolet radiation.
Navy BuOrd	$ 140,000	12 solid rockets to be used in sounding rocket tests.
Smithsonian Institution	$ 100,000	Science and engineering studies of instrumenting an orbiting telescope.
Univ. of Minnesota	$ 60,000	Build a life-support system using plants to generate oxygen; toward development of prototype system.
Vector Mfg. Co.	$ 60,000	Subcarrier oscillator components in the Scout electrical system.

AF Office of Scientific Research, Washington 25, D.C.

Research on hypersonic high temperature air wind tunnel, $310,000, **Princeton Univ.**, Princeton, N.J.

Continuation of research on transonic and supersonic flow, $50,000, **Brown Univ.**, Providence 12, R.I.

Continuation of research on aerodynamic and heat transfer studies with evaporative cooling at hypersonic Mach numbers, $70,389, **Univ. of Minnesota**, Minneapolis 14, Minn.

Air Proving Ground Center (ARDC), USAF, Eglin AFB, Fla.

Rocket launching towers, $134,303, **Aerojet-General**, Azusa, Calif.

ARMY

Army Ordnance Dist., Los Angeles, 55 S. Grand Ave., Pasadena, Calif.

Engineering and fabrication, $70,000, **Harvey Aluminum, Inc.**, 19200 S. Western Ave., Torrance, Calif.

Design and development, $1,500,000, **North American Aviation**, 6633 Canoga Ave., Canoga Park, Calif.

Rocket engines, $162,583, **North American Aviation**, 6633 Canoga Ave., Canoga Park, Calif.

Army Ordnance Missile Command, Redstone Arsenal, Ala.

Film reading system, $37,765, **Telecomputing Corp.**, 12838 Saticoy St., N. Hollywood, Calif.

Technical assistance for guided missile school instruction, $53,316, **Martin Co.**, P.O. Box 5837, Orlando, Fla.

Solar cells, $34,380, **International Rectifier Corp.**, 1521 E. Grand Ave., El Segundo, Calif.

Amplifiers, modules, power supplies, $40,898, **Beckman Instruments**, 325 N. Nuller Ave., Anaheim, Calif.

Design, fabrication, installation, alignment, and calibration of a multicomponent force measuring system, $80,571, **Baldwin-Lima-Hamilton Corp.**, Electronic & Instrumentation Div., 52 Fourth Ave., Waltham, Mass.

System phototheodolite for photographing moving or stationary targets and recording their position in azimuth, $131,588, **J. W. Fecker, Inc.**, 6592 Hamilton Ave., Pittsburgh 6, Pa.

Army Signal Supply Agency, 225 S. Eighteenth St., Phila. 3, Pa.

Three each ground stations for Courier comm-satellite system, one each satellite checkout facility, $800,000, **ITT Laboratories**, Nutley, N.J.

Vehicular antenna research in the HF region, $46,510, **Thompson Ramo Wooldridge**, Los Angeles, Calif.

Design and test plan for radiosonde, $65,060, **Atlantic Research Corp.**, Alexandria, Va.

Infrared surveillance system, $2,358,670, **HRB-Singer, Inc.** and the **Singer Mfg. Co.**, a Joint Venture, State College, Pa.

Boston Ordnance Dist., Army Base, Boston 10, Mass.

Production of research and development device for use in Nike-Hercules, $33,680, **Raymond Engineering Lab, Inc.**, Middletown, Conn.

Solid propellant spin motor system, Littlejohn Phase II Rocket, $30,130, **Hamilton Standard Div.**, United Aircraft Corp., Windsor Locks, Conn.

New York Ordnance Dist., 770 Broadway, N.Y. 3, N.Y.

Nike-Zeus industrial planning program, $9,950,000, **Western Electric Co., Inc.**, 120 Broadway, N.Y. 5, N.Y.

Study, design, fabrication of nine (9) prototype accelerometer monitors and microminiaturized 3-speed synchro assemblies utilizing size 8 synchros for ground equipment to be used in the Jupiter Guidance System, $97,000, **Bulova Research & Development Labs, Inc.**, 62-10 Woodside Ave., Woodside 77, N.Y.

Study and development of basic research tool applicable to gun launchable guidance systems, $42,000, **Bulova Research & Development Labs, Inc.**, 62-10 Woodside Ave., Woodside 77, N.Y.

Engineering and design services for selection and installation of air handling equipment for a supersonic wind tunnel, $43,409, **Burns & Roe, Inc.**, 160 Broadway, N.Y. 13, N.Y.

R&D study on determination of thermal properties of materials, $42,500, **J. L. Finck Labs**, 440 Rogers Ave., Brooklyn 25, N.Y.

A high density impulse monopropellant study, $60,000, **Reaction Motors**, Denville, N.J.

Feasibility study on vortex combustion, $74,990, **Reaction Motors**, Denville, N.J.

Research in physical and chemical principles affecting high temperature materials for rocket nozzles, $350,000, **Union Carbide Development Co.**, Div. of Union Carbide Corp., 30 East 42nd St., N.Y. 17, N.Y.

NASA

NASA, 1520 H St., N.W., Washington 25, D.C.

Study of varying solid propellant burning rate by means of sonic energy, $85,188, **Acoustica Associates, Inc.**, Mineola, N.Y.

Investigation of the capabilities and limitation of refractory coated materials, $99,134, **T. R. Finn and Co.**, Hawthorne, N.J.

Aspan rocket vehicles, $139,598, **Cooper Development Corp.**, Monrovia, Calif.

NAVY

Office of Naval Research, Washington 25, D.C.

Research on electron activated microminiaturization, $27,550, **Stanford Research Institute**, Menlo Park, Calif.

Research on high precision scattering of nuclear particles and precision studies of nuclear reactions, $169,000, **Univ. of Pittsburgh**, Pa.

Research on co-axial jet-air mixing, $26,092, **Convair**, San Diego, Calif.

Development of magnetic mass spectrometers, $98,610, **Consolidated Systems Corp.**, Monrovia, Calif.

Gaseous-Core Rockets

(CONTINUED FROM PAGE 25)

lant mixture, would be to use rotating magnetic fields to spin the mass of hot ionized fuel, thus providing the centrifugal acceleration necessary for fuel separation.

The figure on page 24 shows diagrams of these three means to contain fissioning fuel. A "centrifugal separator" device seems theoretically feasible, and also more practical than those using the magnetic containment principle, primarily because of the massive electrical equipment needed for the latter. Reactors of the centrifugal type have been the subject of considerable theoretical study, and some of the crucial fuel-separation experiments are now in process at a number of laboratories in this country. It is likely that conclusive demonstration of operational feasibility (positive *or* negative) will be available shortly.

The principal stumbling block for these cavity reactors, however, still seems to be heat transfer, i.e., keeping the cavity walls from melting or eroding away. It appears that the usual conductive and convective heat-transfer components, which give the biggest headaches in chemical rockets, will be far overshadowed by thermal radiation at the high temperatures of interest here.

The only possible loophole in this apparently serious heat-transfer limitation is the chance that the effective thermal emissivity of these gaseous cores may be quite low. Unfortunately, the theoretical analysis of radiation from an energy-producing gas is quite complicated, having perhaps its closest parallel in the astrophysical study of stellar interiors, and this question is not likely to be resolved definitely until some experimental work has been done.

The diagram on page 24 illustrates the principle of a hybrid solid-gaseous system. The purpose of this scheme is to reduce the amount of fissionable fuel which must be mixed with the propellant to provide criticality. This is done by using a sequence of subcritical "conventional" reactors, which are temporarily rendered highly supercritical when a slug of propellant gas containing some gaseous fissionable fuel passes through them. The gas is heated as it passes through each succeeding reactor, becoming hotter and hotter, until it finally issues from the cooled nozzle at a very high temperature.

The two principal drawbacks to this scheme are obvious: First, the crucial radiative wall-heating problem still exists, although it is somewhat relieved by the intermittent nature of the hot gas flow. Second, and more important, it is clear that the solid reactors must also become hot. In fact, because of their higher relative gross mass and much higher cross-section with respect to the gaseous slug of propellant, the solid reactors must necessarily absorb the lion's share of the energy released. The prohibitively large mass of the separate cooling system required (together with the mass of the solid reactors themselves) thus eliminates this scheme from practical consideration.

Shown in diagramatic form on page 24, the "solid-propellant" nuclear fizzler, like its chemical namesake, appears attractive principally because of its simplicity. The "grain," composed of fissionable fuel and a moderating propellant, is kept subcritical before operation by a neutron-absorbing control rod. The system is "ignited" by removing a sufficiently long section of control rod at the nozzle end. This end of the reactor thus becomes sufficiently supercritical to vaporize itself, raising the temperature of the adjoining section, and thereby reducing the neutron absorption cross-section of its control rod sufficiently to produce criticality. A zone of criticality thus propagates up the grain, vaporizing the fuel and moderator as it moves. Unfortunately, however, it turns out that the stable "burning rates" of these configurations are extremely high, approaching those of a bomb rather, than that of a fizzler. Thus, since there is little control possible without a prohibitive degree of complication, the fizzler also appears to be ruled out by practical considerations.

Project Orion Scheme

The diagram on page 24 illustrates the principle of the nuclear bomb-powered rocket, now being studied actively by General Atomic under Project Orion. Rough preliminary analyses indicate the system is penalized by comparatively low average specific impulse, enormous size, and low thrust-to-weight ratio. However, there has been much recent interest in Project Orion, indicating that some solution to these problems may be in the offing.

Finally, although a controlled fusion reaction has not yet been produced even in an experimental configuration, it will nevertheless be an important factor in future propulsion-system considerations. In fact, the "thermonuclear rocket" is considered by some the ultimate rocket powerplant with an operating principle lying within the concepts of present scientific knowledge. Thus, although it is certainly pointless to discuss detailed engineering aspects of the as yet unknown reactor configuration (estimates of oper-

ational target dates for *stationary* powerplants range from 15 to 100 yr), some basic ideas relating to thermonuclear propulsion systems are of interest even at this early date.

Very briefly, the exothermic nuclear fusion process, which eventually forms helium from reactions between deuterium nuclei (the most likely fuel for rocket applications), may be induced by overcoming the electrical Coulomb repulsion between the deuterium's protons. This requires heating the fuel to energies in the range of 10,000 to 100,000 electron volts—a *hundred million* to a *billion* degrees centigrade.

The basic problems involved in the construction of thermonuclear reactors result directly from this temperature requirement, e.g., how to heat the deuterium to these temperatures, how to keep the resulting plasma intact until sufficient time has elapsed for the reaction to occur (of the order of 0.01 to 1 millisec), how to keep impurities out of the deuterium (tiny fractional percentages of heavy nuclei radiate away much of the plasma energy), how to maintain control of the reaction, how to absorb the enormous amounts of radiated energy, etc.

The diagram on page 25 shows one possible form for a fusion rocket, suggested by the author in 1956. The fully-ionized, billion-degree deuterium plasma is held in a longitudinal configuration by the linear magnetic field of a solenoid, the ends being closed off by "magnetic mirrors" of the type now under investigation both in Russia and at the Lawrence Radiation Laboratory here in the U.S. The mirror at the "back" end is, say, 100 times less effective than that at the "front" end, so that the hot ions effuse preferentially out the back. The axial ion velocity component out the exit of this magnetic nozzle is of the order of 10^9 cm/sec. (The effusing electrons would be relativistic, but their thrust contribution would probably be small.)

Although the weight of the "ignition" system necessary to initiate the reaction may be enormous (no really successful method has yet been developed), this does not affect the rocket system weight, since the reactor would probably be started on the ground. One eventual possibility for reducing the enormous mass of magnetic field-generating equipment, suggested by the author in 1956, and recently publicized by Edward Teller of the Lawrence Lab, would be the development of superconducting materials, for the containment field coils, having magnetic field breakdown thresholds higher by an order of magnitude than those presently known.

The configuration shown on page 25 could be used as a "furnace," heating by its neutron and gamma radiation a thick "porous" wall or shield cooled by ordinary hydrogen propellant. The cooled system would have high thrust; but, as in the somewhat similar cavity reactor, propellant "chamber" temperature is fixed by wall cooling limitations. Here, however, in contrast to the cavity reactor, the neutron and gamma radiation (actually hard X-rays called "bremsstahlung") are predominant, the extreme plasma particle velocities and low density resulting in a relatively low level of thermal radiation. This has the effect of improving the wall-cooling situation, since the radiated energy can penetrate the thick wall instead of all being released at the inner surface.

Boost and Sustain Stages

The cooled-wall arrangement, because of its high thrust, could constitute a "first-stage," or boost, powerplant. A "second-stage" interplanetary sustainer would then be formed by dropping the shield, pumps, and hydrogen propellant tanks. No pressure shell is required, since the high plasma pressure is transmitted to the field coils through the magnetic field, and thence to an open framework. The radiated energy would be discarded to space, the comparatively thin field coils and structure absorbing only a tiny fraction. Of course, the coils and structure would require cooling by a rather highly loaded refrigeration system, probably employing two separate fluid loops, e.g., water and liquid hydrogen.

Sustainer thrust is obtained, as indicated earlier, by effusion of the plasma out one end of the reactor. The level of this "second-stage" thrust would, of course, be rather low—one estimate which optimistically assumes superconducting field coils places sustainer thrust-to-weight ratios in the range 10^{-2} to 10^{-3}—but the specific impulse, corresponding to the billion-degree plasma temperature, exceeds a million seconds.

Some idea of the relative potential performance of the systems discussed is indicated by the estimates given in the graph on page 25. The superiority of the thermonuclear system, especially the uncooled "sustainer," is clear. It must be remembered, however, that the science, not to mention the engineering, of fusion reactors is in its pre-infancy. On a much lower level in *both* performance and difficulty, but with feasibility likely to be demonstrated shortly, is the cavity fission reactor. Again, however, it is essential to point out that the large size and operational complexities of these reactors may be prohibitive. This could be especially true when they are compared with somewhat lower performance but much simpler concepts, such as the conventional low-pressure, solid-core reactor or, perhaps, the very promising solid-core reactor which utilizes an isothermal nozzle. ◆◆

Red-Eye—Footsoldier's Anti-aircraft Missile

The three Army men hold components of Red-Eye, the new tube-launched, rocket-powered, infrared-homing missile that will give footsoldiers a weapon against low-flying aircraft. Being jointly developed by the Army, Marine Corps, and Convair-Pomona, the Red-Eye system weighs about 20 lb, has an effective range of up to a mile. A single soldier holds and fires the weapon like a bazooka. Major components of Red-Eye system—left, pistol-grip firing mechanism; middle, the missile; and right, the launching tube.

Plasma Propulsion

(CONTINUED FROM PAGE 33)

than the usual spiral orbit. Storage batteries are required to store the available energy during the portion of the orbit that thrust is not applied. There is also a curve showing the range of operation for chemical propulsion. The 10-day flight-time is for the Hohmann transfer ellipse trajectory which has the maximum possible payload. Shorter flight-times are possible, but result in smaller payload weight ratios.

The table on page 33 gives the optimum flight parameters for a round trip to a lunar orbit starting from a 150-mi-altitude orbit. The payload weight ratio is shown for chemical and several electrical propulsion systems. Times were obtained by computing the optimum operating conditions represented by the maxima of curves of the type shown in the previously cited figure. Flight-time varies approximately as the square of the specific impulse. Thus, for large specific impulses flight-times become very long. Note that for high performance (low specific weight) electrical propulsion systems give flight-times nearly equal to those required for chemical propulsion. These times can be achieved with an electrical system operating at a low specific impulse.

The data in these two figures and the table illustrate the effects of varying the specific impulse on the performance of a space propulsion system. It is clear that specific impulses in the 1500 to 5000-sec range will be most useful for missions contemplated within the gravitational field of the earth.

Having defined a region of specific impulse which is favorable, let us consider possible methods of achieving these specific impulses.

In the analysis of electrical propulsion performance for a particular mission, efficiency of the thrust device is just as important as the efficiency of the power supply, because inefficiencies in either would demand an increase in the amount of power required, and thus an increase in power-supply weight. Therefore, high efficiency must be emphasized in the development of electric propulsion devices.

It is convenient to separate thrust devices into three categories, based upon the type of gases that are used as the propellant and methods of transferring energy to them: These are:

1. Nonconducting gas (nonelectrical).
2. Electrostatic acceleration devices (ion rockets).
3. Neutral plasma devices.

In the nonconducting gas devices, energy is either stored in the fluid in the form of chemical energy, or transferred to the fluid by contact with hot chamber walls. In both cases, maximum specific impulse attainable is limited to rather low values. Ordinary chemical rockets will probably not exceed specific impulses of 400 sec in the near future. A device in which the propellant is heated by contact with the walls has a limiting stagnation temperature determined by the maximum practical temperature of the wall material. This limits specific impulse to values less than 750 sec.

The most widely publicized electrical system is the ion rocket, which uses electrostatic acceleration of ion beams. Atomic ions are formed and accelerated to the desired velocity in an electric field. In order to exert a net force, the accelerating field must act on a region where only one type of charge is present. Therefore, ions and electrons must be separated, and ions alone allowed to flow through the accelerating field. The principles of the ion rocket are well understood, and it is clear that it will be difficult to attain low specific impulses with ion rockets. The lower limit for ion rockets can be determined by practical considerations based upon several fundamental limitations—the ion-space-charge current limitation in the acceleration region, electrode erosion by heavy ion bombardment, and radiation from hot surfaces. The practical lower limit to the specific impulse which can be achieved with ion rockets appears to be above 7500 sec.

Propellant Ionized

In neutral plasma devices, the propellant is a partially or fully ionized gas. The minimum required degree of ionization can be achieved at temperatures above about 3000 K. Electron and ion densities are maintained essentially equal, so there is no net space charge in the gas and space-charge limitations associated with the electrostatic accelerator are avoided. Since the gas is an electrical conductor, it will interact with electromagnetic fields. Electromagnetic fields can therefore be used either to heat the gas to high temperatures or to accelerate it to high velocities. Gas stagnation temperatures which can be achieved are not limited by the temperatures at which the walls can be maintained. Specific impulses greatly in excess of those which can be reached with nonconducting gas devices are therefore attainable.

In principle, neutral plasma devices

can be conceived that operate over a range of specific impulses from below 1000 to above 20,000 sec. Neutral plasma devices may be expected to bridge the gap between the nonconducting gas devices and the ion beam, and to overlap the operating ranges of these devices to some extent. In particular, neutral plasma devices can operate in the range of specific impulses most favorable for flight within the earth's gravitational field.

There are three main loss mechanisms in plasma accelerators. One is similar to the dissociation loss which occurs in the chemical rocket—namely, a certain fraction of the energy input will be carried away by the exhaust gas in the form of chemical or ionization energy. These frozen expansion losses increase with increasing gas temperature in the thrust unit. These losses are largest for the arc-heated plasma jet, and are reduced in devices where electromagnetic acceleration of the gas to high velocities is accomplished without heating the gas to extreme temperatures. Other losses are those due to heat conduction to the walls and those associated with the electrodes. These losses will limit the range of power and specific impulse in which efficient operation can be achieved.

Present indications are that several types of plasma accelerators can be designed to operate in the specific impulse range between 1500 and 5000 sec, as well as at higher specific impulse. The figures on pages 32–33 show such neutral plasma accelerators, and give an indication of the regions in which efficient operation can be achieved for each device. There are also possible designs that do not use electrodes, such as an accelerator which operates on a traveling wave principle, or a high-frequency electrodeless discharge.

The figure on page 32 shows an arc jet and its efficient operating range. The schematic drawing indicates the basic features of the arc jet. Propellant gas is heated by Joule heating as it flows through the electric arc and then passes through the mixing chamber, where sufficient time is allowed for nonuniformities in the gas temperature to even out. The hot gas is then expanded in a conventional nozzle.

Two limitations to the efficient operating range of the arc jet have been drawn, assuming helium as the propellant gas. The line labeled "energy loss to walls > 50%" is a limitation due to heat transfer to the walls. Operation at power levels below this line would correspond to an efficiency less than 50 per cent.

At higher specific impulse, inefficiencies due to frozen expansion in the exhaust nozzle become more important. It can be shown that there will always be frozen expansions at these exhaust velocities. A line has been drawn indicating the maximum specific impulse at which the thrust efficiency due to frozen expansion losses alone becomes less than 50 per cent. In drawing both these limiting lines, the minimum practical nozzle diameter was taken to be 1 cm. The electric power level shown in this figure is the operating power level of the arc. The average power level can be lower than this by a factor of 10 to 100, since energy storage can be used and the arc operated intermittently.

A laboratory model of the arc jet has been operating at the Avco-Everett Research Laboratory. The region in which experiments have been performed is also shown in the figure. Measured efficiencies throughout this range were greater than 50 per cent.

The figure on page 32 shows a schematic diagram of the low-temperature magnetohydrodynamic accelerator and the limits of the operating range. Propellant gas must be preheated to a temperature of at least 3000 K by an electric current in an arc jet chamber similar to the one just described. This temperature is low compared to stagnation temperature. The accelerator utilizes magnetohydrodynamic forces to accelerate propellant gas. Currents are made to flow through the gas between electrodes placed at the top and bottom of the duct. A magnetic field traverses the duct perpendicularly to the plane of the figure. These currents in the presence of the magnetic field produce a force which accelerates the gas. Gas temperature can be maintained low throughout the accelerator, thus minimizing frozen expansion losses. This device extends the specific impulse range for the arc jet.

Operational Limits

Limitations to the operating range of this device are shown. At low specific impulses, important losses occur at the electrode surfaces. These are associated with the power dissipated by the current flowing through the voltage drop at the electrodes. At higher specific impulses, the dominant loss mechanism is viscous dissipation at the walls of the duct. Maximizing the region of efficient operation of this device leads to small channel areas, high gas densities, and strong magnetic fields.

The top left figure on page 33 shows the MHD shock tube and its operating range. This device operates on a pulsed basis. When the switch shown in the circuit diagram is closed, a current is formed between the electrodes in the annulus gap. As the capacitor

discharges, the current sheet in the gas will expand, pushing the gas in the annulus ahead of it and setting up a shock wave. The coils surrounding the device produce a weak axial magnetic field which forms a magnetic bottle and inhibits energy losses to the walls. Note that the gas between the shock wave and the current sheet is both heated and given directed motion. In this device, about half the energy goes into directed motion, and the other half into thermal energy. The gas expansion at the exhaust end of the chamber permits recovery of some of this thermal energy. Frozen expansion losses are much smaller than for the arc jet, because only half the energy is in heat.

Electrode Losses

The principal limitation on the operating range of this device is due to electrode losses. A limiting line indicating 50 per cent thrust efficiency has been drawn in terms of the average power level and specific impulse. Average power level has been related to the instantaneous operating conditions by the assumption that the gas flows into the chamber continuously, and that the condenser is discharged when the chamber is full. If valves were used to control the flow of gas into the annulus, lower average power levels could be achieved.

An experimental model of this apparatus has been operated at Avco-Everett. The range in which experimental data has been obtained is indicated in the figure. However, thrust efficiency has not been measured.

The last device, the magnetohydrodynamic rotor, is shown on page 33. This device is similar to the MHD shock tube, and is also a pulsed device. When the switch in the circuit is closed, a current is formed between the electrodes in the annulus gap. The electrodes are short concentric cylinders. The major differences between the two devices arise from the presence of a strong axial magnetic field. The interaction of this field and the radial current between the electrodes produces an azimuthal force, accelerating the gas initially to a high rotational velocity. The rotational motion of the gas is then converted into axial motion as it expands through the nozzle. The principal limitation to the operating range of this device is also due to electrode losses. The operating range is similar to the one for the MHD shock tube.

In comparison with the shock tube, the presence of rotational gas motion increases the complexity of the flow problem to some extent. There are, however, two advantages to this system: (1) Reduced frozen expansion losses, since the gas is initially not accelerated rapidly in the axial direction; and (2) simplified electric circuitry. Since the axial gas velocity is lower, the gas spends a longer time in the initial accelerating region. Energy is therefore fed into the gas at a lower rate. This considerably reduces problems associated with the external circuit, since lower peak power levels are required and the circuit rise time requirements are less stringent.

A device which simulates the initial stage of this propulsion system (the production of high rotational velocities by a similar magnetic field configuration) has been used in fusion research by Baker and his co-workers. They obtained gas velocities corresponding to specific impulses of 3000 sec together with good MHD containment.

The four thrust chambers described serve to illustrate the large variety of methods for producing propulsion with neutral plasmas. There are other designs operating on different principles—for example, electrodeless systems that accelerate the gas along a traveling wave tube or by strong high-frequency pulses.

Our evaluation of the efficient range of operation was based on only a theoretical analysis. So far, not even a prototype propulsion system has been operating for a sufficient time to indicate the major problems that will arise. Problems such as flow stability and electrode and wall erosion remain to be investigated. And reliable running time of a year must be demonstrated for a fully operational device.

While plasma propulsion is still in the exploratory stages, the increased interest in the important specific impulse range from 1500 to 5000 sec should serve as an impetus to attain these goals. ◆◆

NBS Programs, New Calibration Service

The National Bureau of Standards has in progress programs of basic and applied research on the primary processes of corrosion and the properties of semiconductors; a fuel-flow-rate standardization program including a study of flowmeter calibration techniques in the range 20 to 100,000 lb/hr; and a new vibration-pickup calibration service for the range 10 to 2000 cps at accelerations up to 10 g. Previously available on a limited basis only, this latter service will provide industrial and government groups with a working standard for pickups, especially those used in missile and space-vehicle testing.

International scene

Sedov Heads IAF for 1960

International Academy of Astronautics to Be Formed

LONDON—Leonid Sedov, chairman of the Commission for Astronautics of the Soviet Academy of Sciences, was unanimously elected president of the International Astronautical Federation at its 10th Annual Congress here Aug. 31–Sept. 5.

Of equal importance with the election of the first Russian to head the IAF was action taken by the Congress to establish an international Academy of Astronautics, to be made up of individuals who have distinguished themselves in one of the fields of astronautics or some branch of science fundamental to the exploration of space.

The Congress, which drew a record attendance of more than 650 people from some 45 countries, also saw the admission of nine societies as new members to the IAF; steps taken toward the establishment of an international institute of space law within the framework of the IAF; the naming of a four-member committee to work toward the establishment of a permanent IAF secretariat; and formation of a committee to draw up plans for lecture tours by eminent astronautical scientists to be co-sponsored by UNESCO and the IAF.

IAF vice-presidents for the coming year will be Col. John P. Stapp, ARS president, who headed the American delegation to the Congress; A. Hjerstrand of Sweden; L. R. Shepherd, chairman of the BIS Council; Eugen Saenger of Germany; and Gen. P. J. Bergeron of the French Astronautical Society.

Andrew G. Haley, 1959 IAF president, was unanimously elected to the new post of general counsel, and was cited in a special resolution of the Congress for his outstanding work in behalf of the IAF and astronautics during the past 10 years.

Adolph Stemmer of Switzerland continues as secretary.

Preparatory work leading to a functioning Academy of Astronautics will be carried out by a founding committee chaired by Theodore von Karman, who will name the other members of the committee. This committee will designate an initial membership in the Academy, which would then commence its work under Dr. von Karman's directorship.

Also, Dr. von Karman will become the editor of *Astronautica Acta* as of the first of next year, taking over from F. Hecht of the Univ. of Vienna, who has capably handled its editorial reins for the past few years. Dr. Hecht announced his resignation, because of the press of other business, during the Congress.

As editor, Dr. von Karman will be assisted by an editorial board consisting of Frank J. Malina of the U.S., Irene Saenger-Bredt of Germany, Dr. Sedov, and Prof. Siestrunck of France. *Astronautica Acta,* continuing to be published by Springer-Verlag in Vienna, will become the organ of the Academy of Astronautics when the Academy begins to function. Until then, it will continue as the IAF publication. Springer-Verlag will continue to publish IAF proceedings as heretofore.

A very sad note at the Congress was the untimely death during the meeting of IAF vice-president K. Zarankiewicz of Poland. Prof. Zarankiewicz, long an active participant in the Federation, was stricken with a heart attack while presiding at the closing business session, and died a few minutes later.

Admitted as voting members of the IAF during the Congress were the Belgian Astronautical Society, the Commission on Astronautics of the Czech Academy of Sciences, and the Indian Astronautical Society. In addition, the two Canadian astronautical societies were both admitted as members, with each permitted to cast the Canadian vote on an alternating basis from year to year. The Aero-Space Medical Assn. of the U.S., the Astronautical Society of Rome, and two Portuguese astronautical societies were admitted as nonvoting members, while an Iranian delegation was given observer status.

A major step was taken toward the establishment of a permanent IAF secretariat with the formation of a four-member committee, headed by L. J. Carter, BIS secretary, to deal with the problem. The committee hopes to find a permanent home for the Federation within the next few months. Paris will receive first consideration, but other cities, such as Rome and Geneva, will also be studied.

Growing acceptance of the IAF as an important international astronautical body was indicated by the formation of a special committee, headed by ARS board member Martin Summerfield, to work with UNESCO in establishing a series of traveling lectureships by prominent astronautical scientists. These will be sponsored jointly by UNESCO and the IAF. It is hoped that the initial lectures will be delivered at the 11th IAF Congress in Stockholm, Sweden, next year.

The Stockholm meeting will be held Aug. 15–20, 1960, with the 12th Congress the following year set for the U.S. at a time and in a location to be designated at a later date. ARS will be the host society for the 1961 Congress.

The sharp increase in ARS membership in the IAF during the past year has resulted in an increase in ARS dues, the sum rising from $1500 this year to $2600 for 1960. The Russian delegation has been assessed $500 for the coming year.

One other important development at the meeting was the formation of an ad hoc committee to work toward the establishment of an international institute of space law within the IAF

The scene at opening plenary session of the 10th International Astronautical Congress in London Aug. 31.

framework. The committee is headed by C. N. Shawcross of Great Britain. The resolution calling for establishment of the institute grew out of the Second Annual Space Law Colloquium, organized by IAF president Andrew G. Haley. The colloquium, held at the famous Lincoln's Inn, for generations the center of England's legal profession, attracted a large attendance, and the colloquia are rapidly becoming Congress high points.

The American delegation to the Congress numbered more than 100 people, and included, in addition to Col. Stapp, Drs. Summerfield, von Karman, and Malina, four congressmen, NASA deputy administrator Hugh Dryden, COSPAR vice-chairman Richard W. Porter, and three members of the ARS national headquarters staff. More than 60 members of the American delegation flew to London on a specially chartered ARS plane.

The inaugural paper at the meeting was delivered by Dr. Dryden. He chose as his topic, "Global Aspects of Space Exploration," and noted that astronautics would inevitably provide enormous benefits to all mankind, rather than to any single nation or group of nations.

The opening plenary session was also addressed by official representatives of the Natural Sciences Div. of UNESCO and of the International Telecommunications Union, both of which sent observers to the Congress. The Congress was opened by the Rt. Hon. Aubrey Jones, British Minister of Supply.

Some 80 technical papers were presented at the meeting in 15 technical sessions, and a number of other papers were delivered at the Space Law Colloquium. Of outstanding interest among the American papers were those by Milton W. Rosen and F. C. Schwenk, on Project Nova (Sept. 1959 Astronautics, page 20); by Dean R. Chapman, on manned spacecraft re-entry problems; and by W. W. T. Crane, who gave the first full-scale report on the Snap III radio-isotope auxiliary power unit.

Attendees at the meeting, held in the scholarly atmosphere of Church House, Westminster, also had a full schedule of social events to choose from. Among these were BIS, British Government, and ARS receptions; an all-day trip to Windsor Castle, which included a boat trip on the Thames; and the gala banquet which wound up the Congress.

The BIS, host society for the Congress, did an outstanding job in arranging the business and technical sessions, handling registrations, and taking care of the hundreds of other details necessary to assure that a large meeting of this type runs smoothly. Under the able leadership of Dr. Shepherd, his charming wife (who had a major role in arranging the ladies' programs at the meeting), and the indefatigable L. J. Carter, BIS secretary, the job was done—and done well.

The three-day British Commonwealth Spaceflight Symposium, which immediately preceded the IAF Congress, provided an interesting backdrop for the international meeting, revealing for the first time the full extent of British astronautical projects. The meeting drew an attendance of more than 200, with only 75 or 80 originally expected. However, government participation in the symposium was disappointing.

—Irwin Hersey

Hugh Dryden of NASA delivers 10th Congress inaugural paper. At his left, IAF vice-president Leslie R. Shepherd; at his right, IAF president Andrew G. Haley.

Left to right, ARS delegates John P. Stapp and Frank Malina and AAS delegates Robert Haviland and George Arthur at one of the business sessions.

The three Russian delegates to the 10th Congress—from left, V. I. Krassovsky, K. F. Ogorodnikov, and IAF president-elect Leonid I. Sedov—register for the meeting.

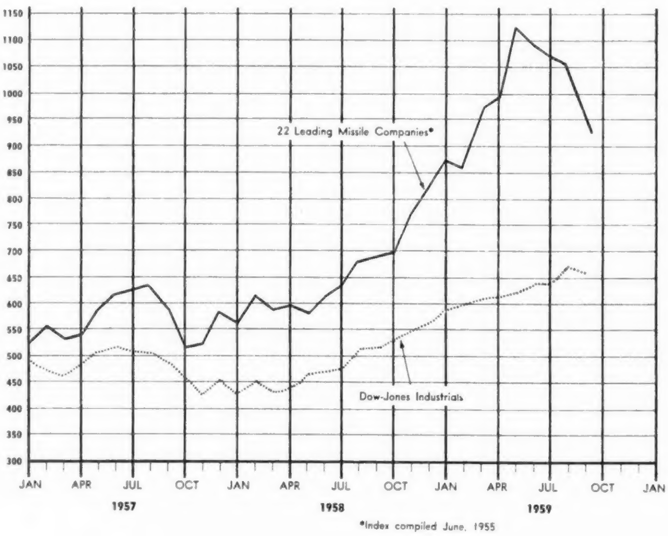
Missile market

BY JEROME M. PUSTILNIK, Financial Editor

POLITICAL news, as it often does, dominated the securities markets last month as investors and speculators weighed the implications of the planned Eisenhower-Khrushchev visits. Uncertainty—always unsettling—coinciding with the announcement of two contract cancellations, battered down share prices to give the Missile Index its sharpest monthly setback in almost two years. Not a single component of the Index escaped damage as it slumped 12.3 per cent, contrasted with a 1.8 per cent decline for the Dow-Jones Industrial Average.

Although political prognostication is not the province of this column, we believe the cold war will continue as relentlessly as during the past 14 yr. Laos and India, the most recent international sore spots, are painful reminders of Communism's belligerency. These new eruptions blemish the smooth appearance of the Washington-Moscow meetings.

THE MARKET AT A GLANCE



	September 1959	August 1959	% Change	September 1958	% Change
Dow-Jones Industrials	663	675	−1.8	509	+30.3
Missile Index	929	1059	−12.3	682	+36.3

In the meantime, missile securities suddenly have lost their former popularity, which could be regained quickly. This would not be an unusual stock market phenomenon. In fact, one of the market's interesting anomalies is the price rise of air-conditioning and soft drink securities that regularly accompanies the summer temperature rise, followed, just as regularly, by price declines as cold weather returns. Securities of defense companies experience the same cycle as apprehension over the cold war waxes and wanes. Therefore, just as it is usually a good idea to buy air-conditioning and soft drink common shares in the dead of winter, when most people, shivering, don't want them, it seems that missile industry securities, currently out of favor with investors, are attractive at this time. *Northrop Corporation*, mentioned in the last issue, is particularly noteworthy.

Northrop has several similarities with the Martin Company, discussed in last month's column. (This similarity extends to a revealing name change—dropping the word "Aircraft" from the corporate title.) Management noted and took early action in the transition from manned aircraft to missiles. Today, missile activities contribute a substantial percentage of sales, as the product mix has changed dramatically.

As recently as 1954 one plane, the Scorpion F-89, accounted for almost 60 per cent of Northrop's sales. But in fiscal 1958 missiles and electronics contributed 41 per cent of sales, drones 16 per cent, manned aircraft only 38 per cent and other activities the balance. Norair, the company's largest division, produces frames for the Snark missile; the new T-38 twin-jet trainer; and subassemblies for the 707, KC-135, and the F-101. A military twin-jet fighter version of the T-38 has recently been introduced, for sale to NATO countries and our other allies as an economical high-performance aircraft.

Nortronics Div. manufactures the guidance system and ground support equipment for the Snark, as well as the mechanical GSE and the airframe for the Hawk missile, as a major Raytheon subcontractor. Dadico, a digital automatic tape intelligence checkout system, is another Nortronics development. It has proved very useful in high-speed checkouts of systems contained in many different missiles. It is management's desire that Nortronics, one day, be the company's largest division. Intensive R&D work on thermoelectric refrigeration processes, infrared devices, and air safety systems give promise this hope will be realized.

Radioplane Div., the world's leading producer of target and surveillance drones, is doing important work on the recovery and landing of space vehicles, including work on Project Mercury.

A leader in the worldwide engineering and installation of long-range communications systems, Page Communications Engineers, recently became a wholly owned subsidiary. Page's current annual sales exceed $16 million, and add potentially significant growth prospects to Northrop. This subsidiary recently received a $10 million contract for a multichannel troposcatter complex.

Though sales in the fiscal year just ended were about the same as 1958's $256 million, net income improved as profit margins widened. Net per share will be about $4.00 on the greater number of shares outstanding.

While the company's Snark program will phase out over the next two years, modification work and new pro-

grams, together with orders for the T-38, and its NATO fighter version, will probably take up the slack. Another major missile contract is expected to develop from one of the many proposals the company has before the services. The major push to expand electronics work will continue, and over the next few years this portion of Northrop's volume is expected to get up as high as 50 per cent.

With the stock selling at only about 7.5 times earnings in spite of a radically altered product mix that emphasizes electronics and similar growth areas, and with a dividend that yields more than 5 per cent and is more than 2.5 times covered by earnings, Northrop would seem to represent an outstanding opportunity for income and capital gains in today's troubled missile market.

Listed on the New York Stock Exchange, Northrop's 1,795,492 shares of common stock have $16.4 million of debt ahead of them. The debt is in the form of two issues of convertible debentures, also listed on the New York Stock Exchange.

Missile Stock Studies

Recent reports on the following companies or industries in italics have been prepared by the investment or brokerage firms specified. Ordinarily, readers can obtain a copy of the study desired by writing to the firm.

Avco Corp., Eastman Dillon, Union Securities, N.Y.C.

Grumman Aircraft, Chace, Whiteside & Winslow, N.Y.C.

Laboratory for Electronics, Gregory & Sons, N.Y.C.

Westinghouse Electric, Pershing & Co., N.Y.C.

Boundary Conditions

(CONTINUED FROM PAGE 29)

where the A's are numerical coefficients which include material strengths, densities, tank pressure, vehicle acceleration, and other structural factors pertinent to the component of interest. The symbol, ρ_p, denotes propellant density; I_{sp} is effective propellant specific impulse; and K_r is the specific power output of the nuclear rocket motor.

Another relation between gross vehicle mass (m_o) and propellant mass (m_p) is found from the mass-ratio equation for rocket flight, as $m_o/m_o - m_p = exp\,[v_c/g_c I_{sp}]$, where v_c denotes the "characteristic" velocity capability of the vehicle. It is clear that propellant mass can be dropped by combining these two equations to obtain a relation between vehicle per-

formance, as measured by v_c and m_L; propellant performance, through I_{sp}; and nuclear-rocket motor performance, given by K_r. This is found to be approximately:

$$exp[-v_c/g_c I_{sp}] = \frac{A_t}{\rho_p} + \frac{A_{pe}}{\beta_p I_{sp}} + \frac{A_r I_{sp}}{K_r} + \frac{m_L}{m_o}$$

Using numerical values for the A's, based upon present state of the art for large rocket vehicles, this becomes the following, for I_{sp} in sec and K_r in Mw/lb:

$$exp[-v_c/g_c I_{sp}] = \left[\frac{m_L}{m_o} + \frac{1}{\rho_p}\right] + 4.5 \times 10^{-5} \frac{I_{sp}}{K_r}$$

It can now be seen that increasing the rocket motor specific power (K_r) for fixed specific impulse propellant density, and for deadload fraction will yield improved performance as measured by increasing characteristic vehicle velocity (v_c).

Our first thought, then, is that we should try to develop nuclear-rocket motors with values of specific power (K_r) as large as possible. This assumption can be tested through numerical calculations for various values of I_{sp} and m_L/m_o by plotting the mass ratio exponent $v_c/g_c I_{sp}$ as a function of K_r.

The graph on page 28 shows such a plot for an assumed value of 0.2 for the term, $(m_L/m_o + 1/\rho_p)$, for a wide range of propellant performance. From this presentation, it is clear that rocket motor specific power must be above about 0.5 Mw/lb for useful vehicle performance, but that values above roughly 1.5 Mw/lb yield little gain while imposing a severe problem on the reactor designer. It seems that a K_r of about 1 Mw/lb represents a *reasonable* value for design purposes.

Let us choose this value and use it to test the effect of propellant performance (I_{sp}) on vehicle performance by further numerical computations. We cannot draw general conclusions quite as directly from these numerical results as from those of the graph on page 28 for the following reason: The limiting factor in almost every conceivable nuclear-rocket motor is the peak operating temperature. For a given operating temperature, propellant specific impulse depends roughly inversely on the square root of the propellant gas molecular weight. But it is an experimental fact that propellants which yield low molecular weight gases also have low liquid densities. The result of this interconnection of properties is that, for a given temperature, the low-density propellant which gives high specific impulse also gives a lower value of deadload fraction (m_L/m_o) for a given value of $(m_L/m_o + 1/\rho_p)$, for which the numerical calculations are made.

Taking this into account leads to the graph of missions on page 29, which gives performance curves for the two propellants which best typify the range of interest for nuclear rockets—hydrogen (H_2) with $\rho_p \simeq$ 4.4 lb/ft^3 and ammonia (NH_3) with $\rho_p \simeq$ 44 lb/ft^3. Also shown on the graph are approximate values of the vehicle characteristic velocity required for several trips of interest within the solar system by use of single-stage ground-launched vehicles. Each of the missions shown includes powered takeoff and landing at departure and all intermediate points.

This graph shows that nearly all of the cited solar-system missions can be accomplished with a single-stage vehicle of reasonable load capacity if propellant specific impulse of 1000 to 2500 sec with ammonia propellant or 2000 to 5000 sec with hydrogen is obtainable.

It is not quite fair, of course, to talk about this desirable range of performance without giving at least some passing consideration to the problems of its attainment. The primary determining parameter is the gas temperature necessary for the achievement of high I_{sp}. This can be estimated by straightforward calculation up to temperatures of the order of 6000 R. Beyond this point, the propellant gases of interest begin to dissociate, and it is necessary to include the rate effects in nozzle recombination for accurate estimates of effective specific impulse. Fortunately, the recombination rates for hydrogen, the principal component of all propellants of interest in nuclear rocketry, are so rapid that the assumption of instantaneous equilibrium in the flow is fairly good and about 80 per cent of the energy put into the propellant upstream of the nozzle will be recovered as kinetic energy of the exhaust.

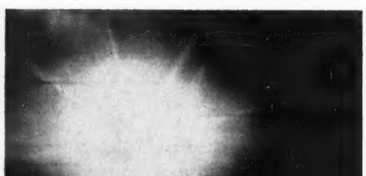
Specific Impulses

Using this assumption for both nitrogen and hydrogen, propellant specific impulse has been estimated in the graph on page 29 for temperatures up to 50,000 R for an isentropic nozzle expansion efficiency of 80 per cent. Ionization energy is appreciable above about 35,000 R, but is likely to be difficult to recover as bulk kinetic energy in the nozzle flow, and has been neglected in these calculations. The graph shows that the desirable range of specific impulse for either NH_3 or H_2 can be attained if it is possible to heat the gases to peak temperature in the range 20,000 to 60,000 R. The bar chart above this graph delineates the physically practical range of solid, liquid, and gaseous-reactor fuels.

It is clear from the chart that the desirable temperature range is beyond the capabilities of solid or liquid nuclear fuels, and that we are forced to consider gas-fueled systems, either for direct heat exchange or for direct conversion of nuclear to electrical power.

One of the oldest concepts in nuclear rocketry is that of the gaseous reactor, first presented in the open literature in 1949 by L. R. Shepherd and A. V. Cleaver. The basic idea is a very simple one. Propellant is pumped into the heat-generating region, a large cavity within a thick neutron reflector-moderator. Fissionable fuel is pumped in simultaneously, a state of nuclear criticality is reached, and fissions occur in the gaseous mixture within the core. The heated gas then leaves through an exit nozzle. This arrangement is closely analogous to the ordinary chemical-rocket motor, for here, as in the chemical rocket, the walls need not be hotter than the propellant gas, as is the case for the heat-exchanger-reactor, and in principle the nuclear "combustion" temperature is limited only by the energy of the fis-

Earth and Sun from Space



This photo shows the sun and the earth's curvature simultaneously from a point some 300 mi high. First of its kind, the picture was taken from GE nose cone in a Thor flight last July.

sion fragments themselves—an equivalent 10^{12} R!

In reality, nuclear and thermal radiation losses to the walls of the cavity core and consequent problems of wall cooling will limit the maximum gas temperature to very much less than fission-fragment kinetic temperatures. Since radiation losses depend upon the gas constituents, system size, and geometry used, no single number can be given as a limiting figure. Indeed no number is yet known with any confidence for such a limit value.

However, recent studies made by E. Saenger on radiation transport in light and heavy atom plasmas indicate that temperatures in the desirable high range ($20{,}000 < T_c < 60{,}000$ R) could be achieved in such a system.

The trouble with this device is just that it *is* gaseous. The gases tend to be well-mixed in the core, and therefore the fissionable material leaves the reactor right along with the heated propellant. This is a serious objection only because fissionable fuel is so expensive, highly enriched U-235 costing about $8000 per pound. A loss of 1000 lb of fuel would cost $8-million, probably about as much as could justifiably be spent in flying a multimillion dollar rocket vehicle.

But what sort of vehicle could we propel with this amount of fuel?

The performance of a gaseous-reactor-powered spaceship can be estimated rather simply in terms of the perfect gas law and conditions in the reactor core, using this relationship: $P_c = \rho_m R_u T_c / M_m$ where ρ_m is bulk gas density within the core, M_m is bulk molecular weight, R_u is the universal gas constant, and P_c and T_c are core-gas pressure and temperature, respectively. By the ordinary equations of nozzle flow, the specific impulse is given as:

$$I_{sp}^2 = \frac{2\bar{\gamma}}{g_c(\bar{\gamma} - 1)} \cdot \frac{R_u T_c}{M_m}$$

where $\bar{\gamma}$ is the ratio of specific heats averaged over the expansion process. The factor, $R_u T_c / M_m$, can be eliminated by combining these two equations, and a further simplification is possible if one of the I_{sp} terms is written as $I_{sp} = I_{tot}/(m_f + m_p)$, where m_f and m_p denote the mass of fuel and propellant used, respectively. The term, I_{tot}, is just the total impulse ($I_{tot} = Ft_b$) required by the vehicle mission.

Carrying out these manipulations, assuming that $\bar{\gamma} = 5/3$, and that the core will become critical with a fuel density of 0.1 lb fuel/ft^3 (based upon criticality calculations by G. Safonov), leads to this performance equation:

$$\frac{P_c}{I_{sp}} = \frac{I_{tot}}{200(m_f/S)}$$

where S, defined as the ratio of the mean lifetime in the core of a propellant atom to that of a fissionable fuel atom, has been introduced as a "separation factor" to account for attempts to retain unfissioned fuel in the core while letting heated propellant escape. (For no separation, S equals 1; for complete retention of fuel, S equals 0.) Note that this equation is independent of choice of propellant. The numerical factor of 200 arises from use of P_c in units of lb/in^2, m_f in lb, I_{sp} in sec, and I_{tot} in lb-sec.

If we assume that core-gas separation is *not* possible, and specify that P_c/I_{sp} be unity (e.g., $I_{sp} = 500$ sec for $P_c = 500$ lb/in^2), the equation shows that 1000 lb of fissionable fuel can produce only 2×10^5 lb-sec total impulse—about one-tenth of that developed in a V-2 flight.

Fuel Loss Factor

This difficulty can be more readily seen from the graph on page 29, which shows the variation of P_c/I_{sp} with the fuel loss factor (m_f/S) for several vehicle missions. This graph shows clearly that, to apply gaseous heat-exchanger reactors successfully to rocket propulsion, a way must be found to extend the region of practical operation by two or three orders of magnitude beyond that shown in the hatched area. If maximum fuel loss is limited by definition to 1000 lb, say, this means that a separation factor (S) of 10^{-2} to 10^{-3} must be achieved within the core gas mixture.

If hydrogen or ammonia are chosen as propellants, the only obvious physical phenomena which may be exploited to achieve separation are the large differences between atoms of fuel and propellant in mass (e.g., 235 versus 1 or 14) and in the first ionization potential (e.g., about 4 ev for fuel versus 14 ev for propellant). The latter fact means that the fissionable fuel will be highly ionized by thermal excitation as compared with the propellant at temperatures of interest, and it is therefore possible in principle to constrain the fuel atoms by externally generated magnetic field "fences" while allowing the hot but un-ionized propellant atoms to escape from the core.

This simple picture is complicated by the direct ionization of propellant by fission fragments slowing down in the core gases. A more straightforward approach is simply to apply the principle of the cream separator to the mixed gaseous core, using centrifugal forces due to core-gas rotation to provide separation of the light propellant atoms from the heavy fuel atoms. While qualitatively sound, both these conceptual solutions appear quantitatively impractical, or at least extremely difficult of attainment, when diffusion forces associated with relative motion between light and heavy atoms in the core are included in the analysis.

Since analyses to date have been made only for simplified models of the real and rather complex interactions which would take place in such reactors, it is clear that much experimental and further theoretical work must yet be done before sensible conclusions can be drawn about the potential performance capability of the gaseous reactor as a propellant heater.

Another possibility for the achievement of high propellant temperatures arises by applying one of the basic ideas from controlled fusion work to the fission plasmas which would be found in a hot gaseous reactor core. It is hoped that electrical power may some day be produced directly from fusion reactions by the cyclic expansion of a hot, ionized plasma resulting from fusion against the pressure of an externally generated magnetic field enclosing the plasma. If the system is properly arranged—that is, frequency and phase lags properly chosen—the work done by expansion will appear as electrical power in the external circuits. As pointed out by R. L. Aamodt and S. A. Colgate, this concept is equally valid for the interaction of a *fission*-heat-generated plasma with an external field. Thus there is the possibility of producing electrical power directly from fission. Since it may prove possible to reach peak temperatures the order of 50,000 R in the pulsating gaseous core of a fission device, the potential conversion efficiency could become very high by normal standards.

Novel Engine Design

Consider the system as shown in diagram form on page 29. Here the propellant is first used to remove waste heat from the electrical-power-production cycle of the reactor and is heated from its initial temperature T_o to T_w in the process. Assume that a "sink" temperature, T_s—perhaps fixed, for example, by structural limits on the reactor container—characterizes the process. The electrical power produced by cyclic operation between a maximum temperature, T_h, and the sink temperature, T_s, is then supplied to an electrical device such as an arc or electromagnetic accelerator, for increasing the directed or random kinetic energy of the propellant still fur-

ther, and the propellant is heated to an effective peak temperature, T_m.

Analysis of an energy balance on the over-all system shows that T_m is related to the reactor cycle and sink operating temperatures, as follows:

$$\Delta T_g = (T_m - T_o) = \frac{T_h\left(1 - \frac{T_s}{T_w}\right)}{\frac{T_h}{T_w}(1 - \lambda_e + \lambda_e)\frac{T_s}{T_w}}$$

where λ_e is the ratio of actual efficiency achieved in the heat-to-electricity conversion process to the Carnot-cycle efficiency.

As an example of the importance of λ_e in the gaseous-electrical reactor system, let's see what gas temperature rise (ΔT_g) can be attained for these assumed conditions: T_o = 500 R, T_w = 5000 R, T_s = 6000 R, and T_h = 60,000 R. For these values, the equation above reduces to ΔT_g = $4500/(1\text{–}0.9\ \lambda_e)$, from the variation of ΔT_g with λ_e is computed to give the following:

Relative electrical energy efficiency, λ_e	Gas temperature rise ($\Delta T_g = T_m - T_o$), R
1.0	45,000
0.95	33,100
0.9	23,700
0.8	16,100

It is evident that $\lambda_e > 0.8$ is necessary if T_m is ever to become comparable to T_h. Since the hot core gas will irreversibly radiate thermal energy while it is doing work by expansion against the magnetic field pressure, it is evident that λ_e will always be less than unity (the value which would apply for a perfect, reversible Carnot cycle).

The problem of attaining λ_e close to unity is basically just the problem of minimizing the ratio of energy lost by thermal radiation to that generated as electricity in the external circuits. The actual value which can be achieved for this relative electrical-energy-production efficiency will thus be determined by a balance between complex and interacting effects involving the oscillation frequency, the peak plasma temperature, and the atomic characteristics of the oscillating plasma and of the core (fissioning region) walls.

Discussion of these factors is beyond the scope of the present paper, but the potentialities for rocket propulsion, as well as application to other fields, appear so great that it is surely worthwhile to pursue this idea beyond the present conceptual picture given here.

Thus far, we have considered propulsion systems only for ground-launched vehicles. However, in closing, a few remarks on nuclear power for freefall flight seem in order. Certainly any nuclear powerplant which can be used for ground takeoff can also be used in freefall flight. Lack of a high acceleration requirement for freefall flight extends the range of interest and usefulness to include even conventional nuclear/electric powerplants with specific masses the order of thousands of pounds per thermal megawatt.

Acceleration Limit

The results of many studies of ion propulsion using solar generators, solar-electric cells, or nuclear-turbogenerator powerplants has led to a general feeling that freefall flight must involve accelerations of the order of 10^{-4} to 10^{-3} g_c. This is true only so long as the electrical power required is generated by conventional heat-engine equipment and generators. If electrical power can be produced directly from nuclear processes without use of rotating machinery and with high cycle sink temperatures, system specific weight can be lowered greatly and accelerations increased far above the milli-g_c range.

Aside from the gaseous-electrical reactor discussed above, it may prove possible in the future to achieve gains in freefall performance up to perhaps 10^{-2} to 10^{-1} g_c capability by exploitation of the plasma thermocouple now under study at Los Alamos, GE (Schenectady), RCA (Princeton), and MIT. Limitation to accelerations of less than 1 g arises because of the necessity of dumping waste heat by thermal radiators if high propellant performance is desired from this system.

Use of a lightweight, radiator-free propulsion system is possible only if regenerative cooling by the propellant is used to remove energy at the sink temperature. But if regenerative cooling is adopted, the equation for the nuclear-to-electrical-power system diagramed on page 29 applies, and a numerical example will show that the plasma thermocouple inherently cannot both produce high-performance propellant and operate regeneratively.

To illustrate this, assume the following operating conditions: T_h = 6000 R, T_s = 3000 R, T_w = 2500 R, and T_o = 500 R. With these, the gas temperature rise is $\Delta T_g = 2000/(1\text{–}0.5\ \lambda_e)$, and even for Carnot cycle efficiency ($\lambda_e = 1$) the propellant will reach only 4000 R. Details of work on the plasma thermocouple, and further references, are given in the articles by G. M. Grover and K. G. Hernqvist listed as Suggested Additional Reading.

Our rough analysis of the boundary conditions for achievement of reasonable nuclear-rocket performance leads to the following general conclusions:

1. Nuclear-rocket-motor specific power output should be aimed for the range $0.5 < K_r < 1.5$ Mw/lb for ground-launched nuclear-rocket vehicles.

2. Propellant specific impulse should be in the range $1000 < I_{sp} < 2500$ sec for NH_3 and $2000 < I_{sp} < 5000$ sec for H_2 for a useful payload capacity on most missions of interest within the solar system.

3. Achievement of the range of performance given in (1) and (2) forces the use of gaesous reactors, operating at peak temperatures of $20{,}000 < T_c < 60{,}000$ R, whether for direct propellant heating or for the production of electrical power for propulsion.

4. Actual attainment of high performance from gaseous reactors will depend principally upon the engineering solutions found for the control of fissionable fuel distribution and geometry within the reactor core during powered operation.

The usefulness of any general study is simply that of pointing out the areas of interest and the major problems in these areas. The ranges of interest here are clear, and in assessing the possibilities for their attainment we are fortunate and can take heart in that no physical phenomena have yet been found which will inherently prevent us from reaching the desired goals. All that is needed is much hard work.

Suggested Additional Reading

Shepherd, L. R. and Cleaver, A. V., "The Atomic Rocket," Chap. 10 of *Realities of Space Travel*, ed. by L. J. Carter, Putnam, London, 1957.

Bussard, R. W. and DeLauer, R. D., *Nuclear Rocket Propulsion*, Chap. 3 and 9, McGraw-Hill, New York, 1958.

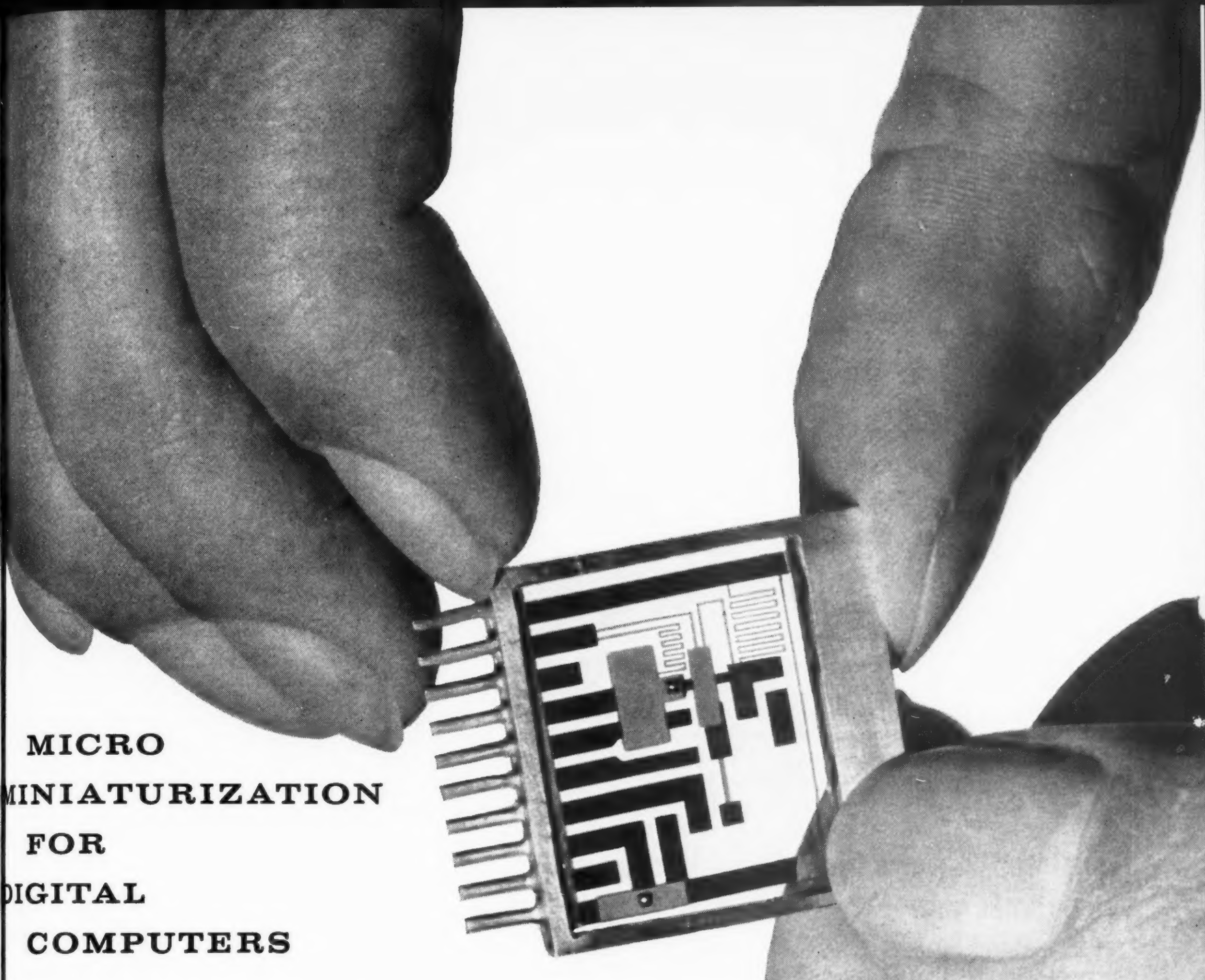
Saenger, E., Strahlungsquellen fur Photonenstrahlantriebe, *Astronautica Acta*, Vol. V, Fasc. 1, 1959, pp. 15–25.

Safonov, G., *The Criticality and Some Potentialities of Cavity Reactors (Abridged)*, The Rand Corp., Res. Memo. RM-1835, July 1955.

Aamodt, R. L. and Colgate, S. A., Plasma Reactor Promises Direct Electric Power, *Nucleonics*, Vol. 15, No. 8, 1957, pp. 50–55.

Grover, G. M., Los Alamos Plasma Thermocouple, *Nucleonics*, Vol. 17, No. 7, 1959, pp. 54–55.

Hernqvist, K. G., Thermionic Converters, *Nucleonics*, Vol 17, No. 7, 1959, pp. 49–53.



MICRO
MINIATURIZATION
FOR
DIGITAL
COMPUTERS

e resistors, 4 capacitors, 4 diodes and 4 transistors…
ll are contained in the complete flip-flop circuit illustrated above.

t the Hughes Research & Development Lab-
atories, dramatic reduction in component
e is symbolic of the advances in the digital
mputer art…advances which are preparing
e digital computer for its role as a system
ntrol in space.

In addition to developing new digital cir-
its and components, Hughes engineers are
iving into other digital computer space mis-
n tasks such as navigation guidance and
ntrol, communications processing and dis-
y, vehicle control, mission programming.

An intensive Hughes program in digital
mputer systems has created openings for creative engineers and physicists with degrees from accredited engineering universities in the following fields:

CIRCUIT and COMPONENT DEVELOPMENT: Digital Computer Analysis, Microcircuitry and Cryogenics, Solid State Physics, Magnetic Storage Devices.

SYSTEMS ENGINEERING: Closed-loop Digital Control, Digital Sensing and Conversion, Radar and Communications Information Processing, Inertial Navigation.

The salary structure for these personnel reflect the exceptional backgrounds required and the unusual challenge of the projects.

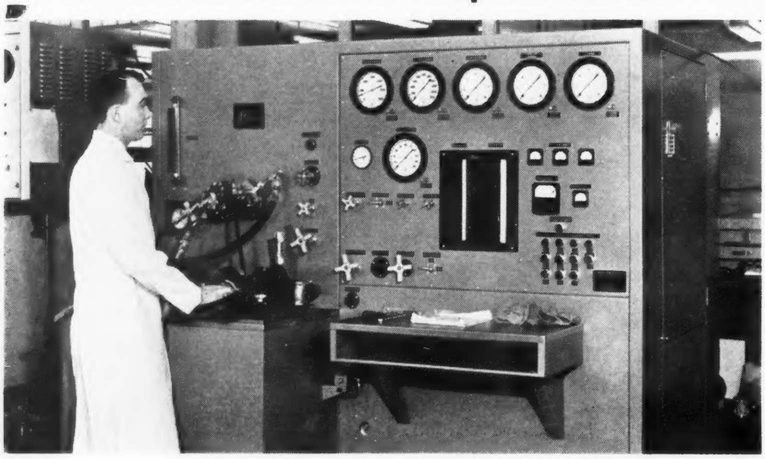
Inquire by writing directly to:
Dr. Allen Puckett, Director
Systems Development Laboratories

HUGHES

Hughes Aircraft Co.,
Culver City 34, California

New equipment and processes

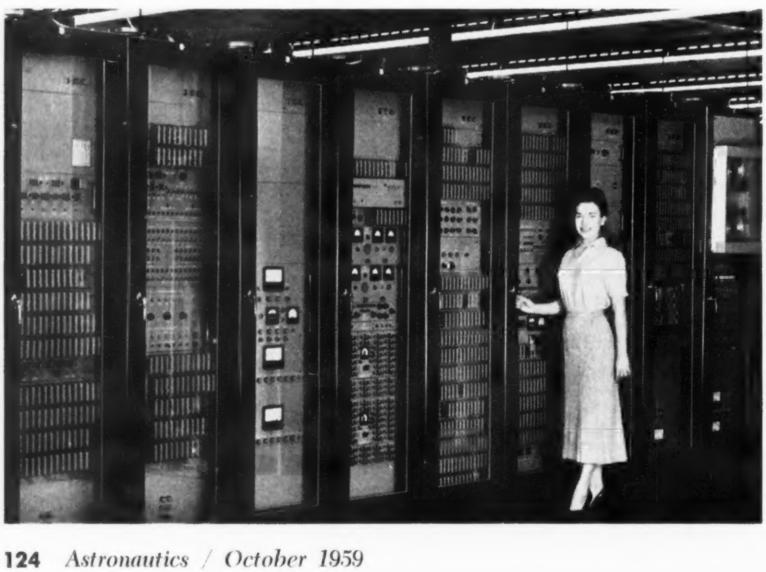
Self-Contained Test Stand for Pumps and Motors



Combined and individual testing of hydraulic pumps and drive motors can be made with the self-contained test stand pictured here at simulated altitudes up to 75,000 ft. Hydraulic system temperature is automatically controlled from 140–170 F. Two variable-area glass-tube flowmeters measure flow over a range of 0.25-10 gpm with an accuracy of ±0.5 per cent full-scale. George L. Nankervis Co., 15400 Fullerton Ave., Detroit 27, Mich.

Translator Converts Digital Flight Data to Computer Format

Flight-test digital data can now be converted into IBM 704 computer format without going through manual data reduction and card input to the computer. The Computer Language Translator, developed by the Electronic Engineering Co., Calif., for Martin-Denver, makes a direct transposition possible. The system translates three types of information: Analog data from an FM discriminator or other source; serial PDM information on a 30 x 30, 45 x 20, or 90 x 10 base; and data from a selected PDM channel. Binary-coded decimal information, and up to 24 bits of identification or fixed address information, can be entered on the output data tape in the same computer format. Also, by interchanging input and output control units, other computer formats or media can be obtained.



Frozen Foamed Resin Used For Potting Electronic Units

Working under a Canadian government development contract, Canadian Westinghouse Co., Ltd., has developed a method of potting complex electronic units in foamed resin, completely filling interstices between components.

The method uses finely powdered resin obtained by freezing a partially reacted foam resin to a brittle state, then grinding it to fine powder. The powder is poured into the cavity to be filled, shaken into the smaller cavities, and as a final step the unit is heated to cause foaming.

Fluoride Coatings Insulate Electrical Circuitry

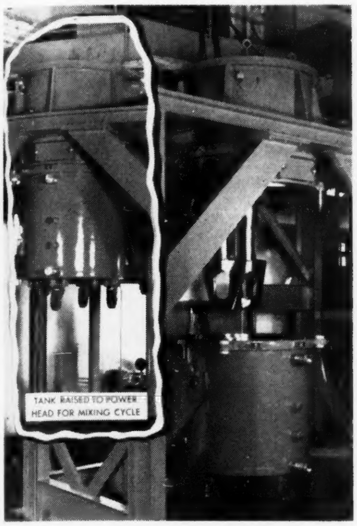
Insulating fluoride coatings can be formed directly on copper and aluminum by exposing these metals to oxidizing carriers of fluorine at temperatures from 300–600 C. Film thickness depends upon forming temperature, concentration of fluorine, and exposure time. Electrical insulation values are on the order of 10^{10} and 10^{11} ohms at room temperature for films 1 to 2 microns thick between probe electrodes 0.25 in. in diam. The insulation does not break down even at 450 v at 500 C. Bell Telephone Laboratories, 463 West St., New York 14, N.Y.

High-Vacuum System: Pressures of 1×10^{-9} mm Hg or lower are attained in a stainless-steel work chamber 12 in. in diam by 18 in. high. The outer chamber, with two 2-in. observation ports, has heating elements, radiation shields, and water cooling coils. Differential pumping permits use of simple seals, eliminating the time and work usually required in pulling up shear metal seals. Kinney Mfg. Div., New York Air Brake Co., 3529 Washington St., Boston 30, Mass.

Servo Analyzer: Multipurpose, transient-free signals are provided by this desk-top analyzer used for testing servo, missile, geophysical, and medical equipment, and for the electrical simulation of mechanical phenomena. The analyzer accepts carrier frequencies from 50 to 5000 cycles, and has an internal carrier source of 5000 cycles. Aetna Electronics Corp., Readington Rd., North Branch, N.J.

Propellant Planetary Mixer: Only 14 ft high, this 250-gal planetary mixer-disperser runs off a four-speed, 20-hp

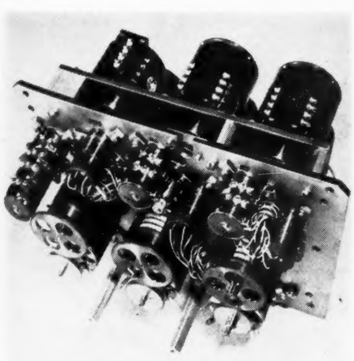
explosion-proof motor. It features wedge-proof paddles, which intermesh for quick kneading and stirring; a temperature-controlled jacket; internal working pressure up to 50 psi; bearings, gears, and other moving parts



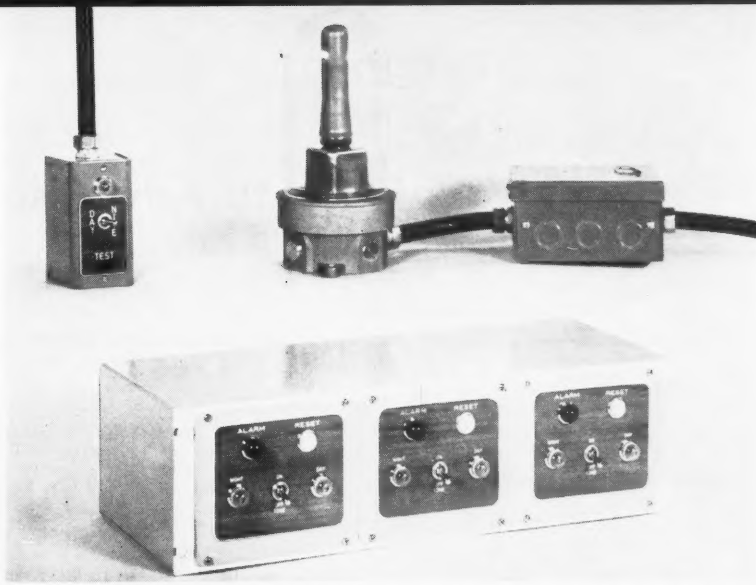
isolated from the batch; and reversible mixing action to smear isolated lumps. Bramley Machinery Corp., 880 River Road, Edgewater, N.J.

Tiny Gears for Sophisticated Vehicles

Linking Sperry Gyroscope's inertial guidance system for NASA's X-15 rocket-powered aircraft to its cockpit control indicators are miniature gear trains like the ones pictured, which are part of a self-contained assembly with amplifier. The speed-reducing spools are about the diameter of a penny and can have a speed ratio of a million to one. Produced by Bowmar Instrument of Fort Wayne, Ind., these mechanisms represent a new level in the state of the art of precision gear bundles.



Bowmar speed-reducing gear trains on miniature integrator for X-15 control.



SWAMI system as an intrusion detector consists of control box at left rear, sensor unit at right rear, and control panel, in foreground, for guard.

SWAMI Pint-Sized Private Eye

Singer Military Products Div. recently demonstrated a miniature radar-like device that detects and measures movement of a body up to several thousand feet away. Actually based on an uhf radio oscillator pulsed at a lf repetition rate, the device detects a body by disturbance its motion causes in the lf repetition rate. A single unit can measure relative speed of a body moving in any direction and absolute speed when it is focused along the body's line of motion. It can be omnidirectional, or directed in a beam by an antenna reflector. Relatively inexpensive and long-lived, the device would seem to have many applications in range safety, traffic control, security, and the like.

Electron Microscope: Now seeing considerable use in metallurgical

studies related to space projects. Philips Electronics Inc., 750 Fulton Ave., Mt. Vernon, N.Y.

Slim Capacitor: Of extended-foil construction, coated with moisture-tight epoxy resin and mounted on a miniature platform, this capacitor can be seated securely on a printed-circuit chassis for withstanding high vibration. Available in 50 v only, in the 0.01–0.33 mfg range. Good-All Electric Mfg. Co., 112 W. 1st., Ogallala, Nebr.

Magnatest Conductivity Meter: A portable eddy-current instrument with hand-held probe, the FM-110, performs a variety of testing jobs, including the determination of hardness, alloy, and heat-treat condition; sorting mixed nonmagnetic metals; checking tensile strength of aluminum; investi-

gating fire damage to aircraft; etc. The unit weighs $4\frac{1}{2}$ lb, and operates off two 1.5-v flashlight batteries. Magnaflux Corp., 7300 W. Lawrence Ave., Chicago 31, Ill.

Index to Advertisers

IMAGINATION IN SPACE

Since Creation, man has looked out on space. At first, unknowing and incurious; then with the beginnings of understanding; now free and able to explore. Yet to move in space calls for wholly new concepts of energy.

This, then, is the working philosophy of Hercules in chemical propulsion: To design and manufacture highly concentrated packages of energy as propellants and rocket motors; each compatible, controllable, predictable; and each perfected for its specific mission.

HERCULES' BACKGROUND: A half-century of creative imagination in the evolution of propellants, from shotgun powder to the manufacture of the propellants for all the U. S. rockets fired during World War II, and now to space propulsion. Hercules facilities today encompass research, design, engineering, and staff organization for the production of the most advanced propellants. Brochure available on request.

Jet propulsion was envisioned as early as 1847 in this design for a rocket plane by Werner von Siemens of Germany. The explosive force of gun cotton was to be used as the source of power. In another of his wood engravings, Brussel-Smith recreates the details of this striking design.

HERCULES POWDER COMPANY
INCORPORATED
900 Market Street, Wilmington 99, Delaware

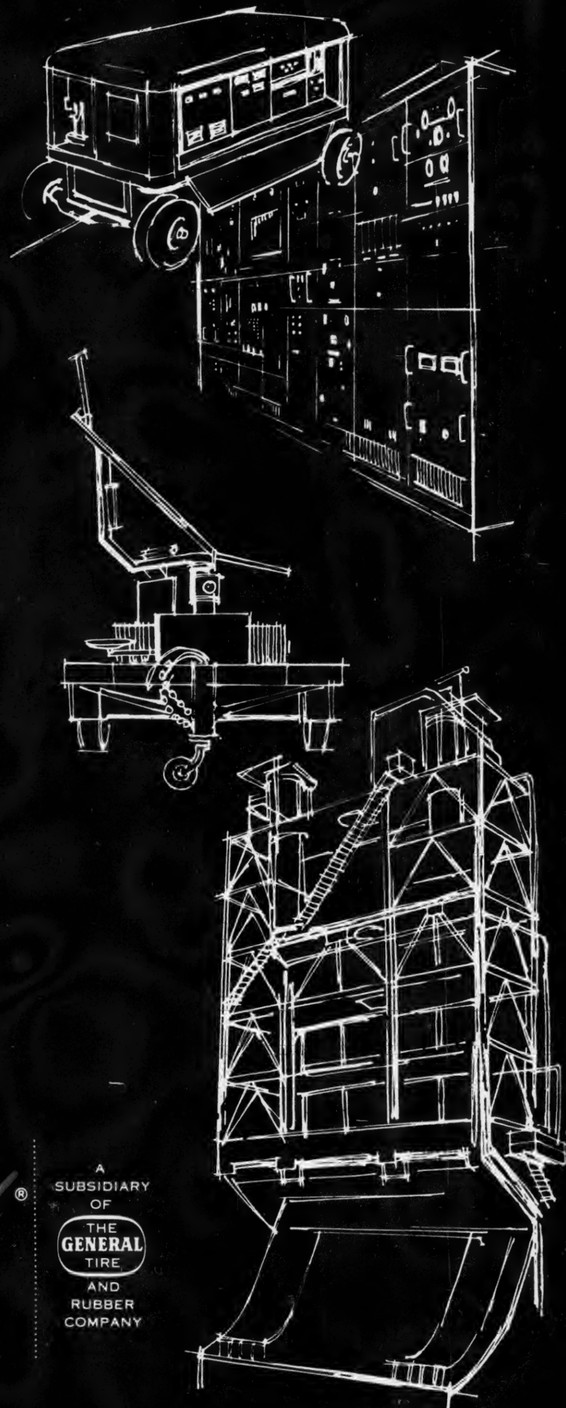
XP59-5

GSE

by AEROJET

Success in the air depends on support from the ground. Aerojet-General designs and manufactures all types of missile, surveillance drone, and space system ground support equipment.

- General Planning and Logistics
- Test and Launching Facilities
- Ground Handling & Servicing Equipment
- Checkout Systems
- Instrumentation and Control
- Data Systems
- Telemetry
- Communication Systems
- Radar Systems
- Space Position Instrumentation
- Miss-Distance Measuring Sets



Aerojet-General®
CORPORATION
Azusa, California

A SUBSIDIARY OF THE GENERAL TIRE AND RUBBER COMPANY

Plants at Azusa, Downey, San Ramon and near Sacramento, California; Frederick, Maryland

Engineers, scientists — investigate outstanding opportunities at Aerojet